

The Hughes External Fixation Device - Studies of its
Biomechanical Properties, Effect on Fracture Healing and
its Clinical Application.

by

CHARLES MICHAEL COURT-BROWN

Thesis presented for the Degree of Doctor of Medicine of
the University of Edinburgh.

March 1984



Contents

Acknowledgements.

Summary.

Introduction..... 1

Section 1.

Chapter 1

History of External Skeletal Fixation.....4

Chapter 2

The Hughes External Fixation Device.

Its Design and Application.....12

Chapter 3

A Review of the Current Concepts of the
Biomechanical Properties of External
Fixation Devices.....15

Chapter 4

The Biomechanical Characteristics of
the Hughes External Fixator.....20

Section 2.

Chapter 1

A Review of the Current Concepts of
Bone Healing and Bone Blood Flow.....39

Chapter 2

Bone Healing and Bone Blood Flow with
the Hughes External Fixator. The
Technique and Results of an Animal
Experiment.....46

Section 3.

Chapter 1

A Review of the Clinical Use of
External Fixation Devices.....60

Chapter 2

A Study of the Clinical Use of the Hughes External Fixator.....	67
--	----

Chapter 3

The Current and Future Use of External Fixation.....	97
---	----

References.....	102
-----------------	-----

Acknowledgements

I am indebted to Professor Sean P.F. Hughes for the guidance and helpful advice that he has given me throughout this study. I am also grateful to Dr. Hamish Law for the particular interest he has taken in the biomechanical section and to Dr. Ian McCarthy for his practical advice. My thanks also go to Mr. Stuart Robertson and Mr. Robert Fleming for their surgical assistance, histological preparation and assistance in setting up the biomechanical study.

I would also like to thank the staff of the animal unit of the Western General Hospital for their enthusiasm and their skill in looking after the rabbits. In this regard I would particularly like to thank Mrs. Joan Robertson and Miss Sharon Rossiter.

My thanks also to Mr. Mike Devlin for his skilled photographic work and to the consultants of the Royal Infirmary of Edinburgh and the Princess Margaret Rose Orthopaedic Hospital for permission to study their patients. Help with statistical analysis was given by Dr. Robin Prescott.

Lastly my thanks to my family for their patience and help during the last three years.

Much of the study was made possible by a generous grant from the Lothian Health Board.

SUMMARY

Summary

External skeletal fixation devices first appeared in clinical practice in the 1850's. Their use has mainly been confined to Europe although North American surgeons developed an interest in the 1930's. In the last few years, however, there has been a reawakening of interest in external fixation in North America and Great Britain leading to a proliferation of different external fixation devices.

Although some experimental work has been done on the biomechanics of some of the more complex fixators very little is known about the optimal configuration of application of most devices. Additionally there is scanty information on the effect that external fixation has on bone healing.

This thesis examines the Hughes unilateral external fixator from three aspects.

1) Its biomechanical properties are examined and the stiffest mode of application defined. The effects of altering this configuration are shown. A comparison is made with the Hoffmann device.

2) The effect of external fixation on bone healing is examined. A small fixator is used to immobilise rabbit tibial osteotomies and the effect on healing and bone blood flow compared with an osteotomy treated with a cast.

3) A prospective study of the clinical use of the Hughes fixator is presented. An analysis is made of the use of the device in treating tibial fractures.

Biomechanical study

This was undertaken using beech as a bone substitute. A

jig was constructed so that different loads could be applied to a simulated fracture held by a Hughes fixator. It was found that the stiffest configuration of the Hughes occurred with the fixator bar close to the limb. The inner pin should be as close to the fracture as possible with the outer pin as far from the fracture as is practical. The effect of altering the location of the bar from a lateral to an antero-medial location as used on the tibia was to lower the stiffness, although only to the level of stiffness gained using a Hoffmann-Vidal double frame. The effect of altering the stiffest configuration was examined.

Bone healing and blood flow study

New Zealand white rabbits were used to investigate bone healing and blood flow using a small external fixator designed for the experiment. Bilateral tibial osteotomies were made and one was stabilised with the small fixator with the contra-lateral osteotomy being treated in a long-leg cast. After a period of between one and ten weeks the rabbits were sacrificed but prior to this were injected with radioactive microspheres. Comparison of the blood flow in the two fracture sites showed a considerable increase in flow in the cast-treated leg after four weeks.

A review of the histology showed that external fixation altered bone healing. The externally fixed leg showed less periosteal reaction but enhanced endochondral ossification and intra-medullary ossification.

Clinical study

A three year prospective study of the use of the Hughes fixator was undertaken. The device was mainly used for the treatment of tibial fractures although humeral fractures and pelvic diastases were also treated. In addition a number of osteotomies and an arthrodesis were

stabilised with the device.

A study of the tibial fractures showed that the eventual outcome of the fracture was dependent on the initial reduction and the length of time that the fixator was applied. Other parameters did not matter.

INTRODUCTION

External skeletal fixation is a method of securing and holding bones or bone fragments using transfixion pins which enter the skeleton percutaneously and are secured to each other by external metal bars. Its earliest origins were in Alsace and France in the middle of last century and European orthopaedic surgeons have maintained a close interest in it since that time. There has however been a recent resurgence of interest in this method of fixation in Great Britain and North America and many different fixators have been invented.

The Hughes external fixator was invented in 1979 because of dissatisfaction with the devices then available. It was felt that a unilateral device was desirable because of the access to the soft tissues which such a device provided. The two unilateral fixators which were then in use were the Wagner (Wagner, 1971) and the Portsmouth (Edge and Denham, 1981). The former device provided good fracture fixation with high stiffness but having been designed for leg lengthening the potential variation in pin position was felt to be inadequate for fracture work. The Portsmouth fixator allowed a greater degree of flexibility as far as pin location was concerned but did not provide good fracture stability. In addition it did not allow for compression or distraction of the fracture although this feature was later incorporated into the design.

The main biomechanical considerations in the development of the Hughes fixator were therefore high stiffness of fracture fixation, adequate variation in pin location and the incorporation of a compression and distraction facility into the device.

Despite widespread acceptance of external fixation devices little is known about the biomechanical properties of many of the external fixators or the effect that external skeletal fixation has on bone healing. Some research has been undertaken into the optimal configurations of the Hoffmann, AO and Oxford devices but this work cannot be extrapolated to other fixators. It is

important to understand the biomechanical characteristics of any fixator in popular use so that not only is its stiffest configuration of application known but the effect of altering this configuration understood. It is also essential to know what effect external fixation might have on fracture healing but with the exception of Hey Groves (1921), Yamagishi and Yoshimura (1955) and White et al (1977), all of whom examined callus production in externally fixed fractures, no work exists in this field.

The Hughes external fixator has been used in Edinburgh since 1979 for a variety of clinical problems. Despite a subjective belief that it gave satisfactory results there were no guidelines as to which fractures should be treated with the fixator and no knowledge as to how it should be applied or how varying its mode of application might alter fracture healing. It was decided to investigate these points and this thesis traces the history of external fixation and then examines the biomechanical properties, the effect on bone healing and the clinical usage of the Hughes device. It is divided into three sections examining:-

A) The biomechanics of the Hughes external fixation frame.

The stiffness of various configurations of the Hughes external fixator under different loading is examined and the configuration which provides the greatest fracture stability is established. The effect on stiffness of altering this configuration is demonstrated as is the effect of changing the location of the fixator. The device is compared with the Hoffmann-Vidal double frame.

B) The biology of external skeletal fixation using a miniature Hughes external fixator.

The New Zealand white rabbit is used as an experimental animal. Studies of bone blood flow and bone healing indicate how the fracture healing response alters with external fixation and why delayed union might occur.

C) A clinical study of the use of the Hughes fixator.

A prospective study of the use of the Hughes external fixator over a three year period is presented. The results of its use in the management of tibial fractures are analysed with reference to the causes of delayed and mal-union. A retrospective study of the earlier use of the Hughes fixator is also presented.

SECTION 1

CHAPTER 1

History of External Skeletal Fixation

The credit for inventing the first external fixator usually goes to Malgaigne of Paris who in 1853 designed a claw for the rigid immobilisation of patellar fractures (Fig 1.1). It was however Rigaud of Strasbourg who first inserted trans-cutaneous transfixion screws and held these by an external band, in this case string. He reported on the successful treatment of an olecranon fracture using this technique (Cucel and Rigaud, 1850). Despite this promising beginning little progress was made in the next forty years although Malgaigne did invent a metal spike held by straps for the treatment of tibial fractures. Berenger-Feraud (1870) also improved Rigaud's technique by joining the trans-cutaneous screws with a wooden bar.

The next milestones in the evolution of external skeletal fixation occurred in the 1890's when Keetley (1893) in London and Parkhill (1894) in Denver invented devices for stabilising long bone diaphyseal fractures. A diagram of Keetley's fixator and its clinical application is shown in Fig 1.2.

It consisted of 2 L-shaped pins of hardened steel plated with silver. After the introduction of one leg of each pin into the bone the other legs of the device were tied together with silver wire. Keetley treated two femoral fractures but removed his fixator after 20 days in the first patient resulting in loss of fracture alignment. The second fracture went on to union.

It is interesting to note that although Keetley was not a proponent of internal fracture fixation because of the high infection rate encountered at that time, he was impressed by certain aspects of his new device. He thought that there were good reasons for believing that a properly cleaned plated steel pin could be left in the tissues for a considerable time without significant problems occurring.

He also realised the potential flexibility of his external system and that the bone ends could be held rigidly or elastically. He commented that as any method

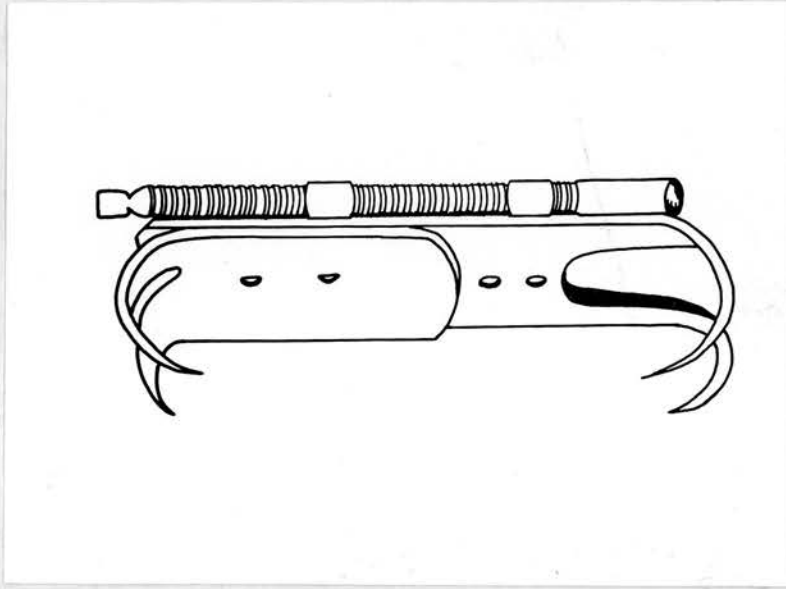


Fig 1.1

Malgaigne's original external fixator invented in 1853. It was designed for the external fixation of the patella and Malgaigne reported that his patients found the clamp to be painful.

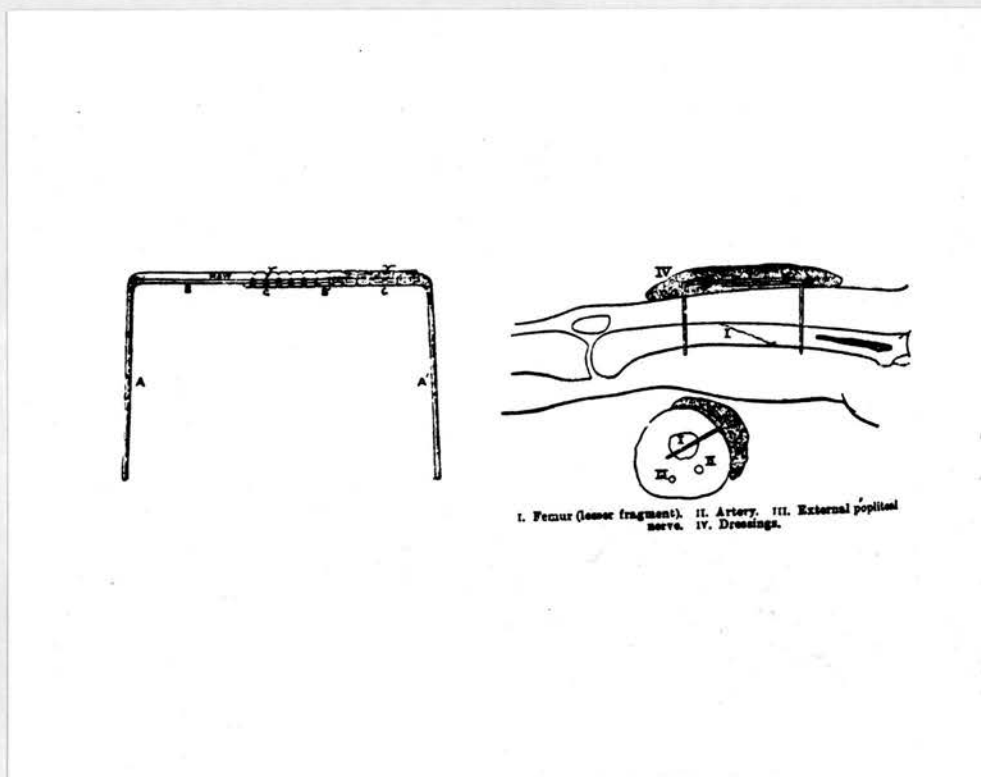


Fig 1.2

Diagrams of Keetley's external fixation device devised in 1893 showing

- A) The exact relationship of the two silver-plated steel pins tied together with silver wire.
- B) The recommended position of application for a femoral fracture.

of using pins could be combined with almost any of the currently available fixation devices, an almost limitless number of possible designs and configurations existed such that almost every surgeon could have his own external fixation method.

Parkhill's device (Fig 1.3) more closely resembles modern devices than Keetley's. He used four silver coated steel transfixion pins clamped to an external metal bar. The device was manufactured in three sizes and in 1898 Parkhill published the results of treating pseudarthroses of the femur, tibia, humerus and radius as well as a fresh patellar fracture. He also suggested that the appropriate size of device was suitable for femoral neck and clavicular fractures. Unlike Keetley's reports the results of Parkhill's work sound a little exaggerated. In his series of 14 pseudarthroses he reported no infection and a 100% union rate compared with a published fracture union rate of 56% at about that time (Gurtl, 1857). He also claimed union times of 5 to 7 weeks for tibial fractures and 6 weeks for established non-unions of the radius and ulna. However despite these enthusiastic claims he seems to have realised the potential versatility of external fixation.

Independently from Parkhill, Lambotte of Antwerp in 1902 also designed a single bar external fixation frame consisting of four transfixion pins clamped to a metal bar. Lambotte however developed the concept further both in the design of the fixation frame and in the type of transfixion pin that he used. In 1913 he published details of a pin holding clamp which is clearly the forerunner of the Hoffmann clamp that is in common use today. His transfixion pins were made of tempered steel and sequentially plated with gold, nickel, tin and latterly nickel-steel.

Lambotte had considerable experience with external fixation and he carefully documented its use in the hand, forearm, humerus, clavicle, tibia and femur. He, like Keetley and Parkhill, was impressed with its relative

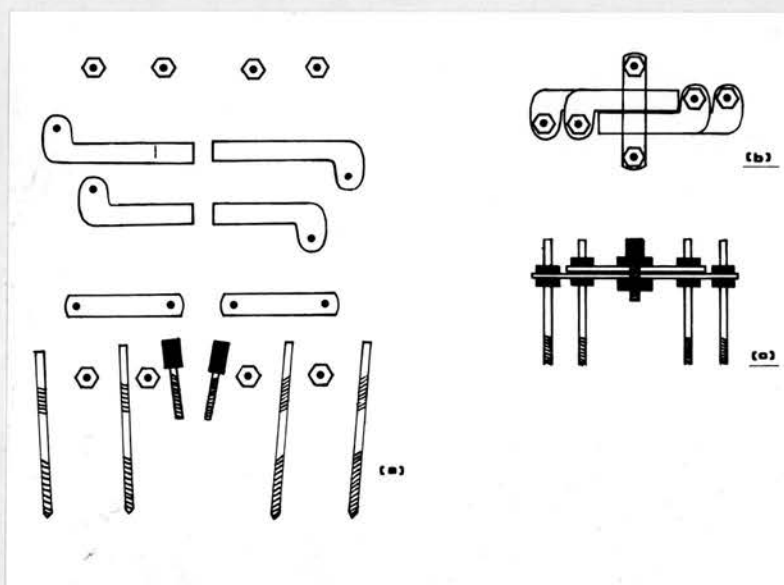


Fig 1.3

Diagrams illustrating Parkhill's external fixator invented in 1894 showing

- A) An exploded view of the device which consisted of 4 steel plates holding transfixion pins. These were secured by two steel cross-plates.
- B) A plan view of the assembled device.
- C) A side view of the assembled device.

ease of application and its versatility. He was however the first surgeon to fully comprehend the particular advantages of external fixation and he stressed the importance of the soft tissue access provided by external fixation.

The evolution of external skeletal fixation continued in North America and in Europe with no real interest being evident in Great Britain where the teachings of Robert Jones had largely convinced surgeons that fractures should be managed by closed techniques. Despite this however Hey Groves in 1921 published the first experimental work on external fixation. He developed a rectangular frame similar in design to the later Charnley clamp. The clamp was applied to osteotomised cat tibiae as part of a study comparing different methods of fracture fixation. He commented that external fixation gave a more "perfect union" than any of the direct fracture fixation methods that he had tried.

Hey Groves applied this principle to the treatment of human tibial fractures using a double transfixion appliance similar to the rectangular device used for the cats. The device was designed for the closed manipulation of fractures with gradual elongation of the side bars being undertaken until the fracture was out to length, at which point alteration of one of the side bars only was supposed to allow fracture reduction. Hey Groves commented that this form of closed manipulation was difficult to perform and he reserved the method for old neglected cases of tibial fracture.

At about this time there was a proliferation of external fixation devices in Europe. Lambret (1910) designed a rectangular device similar to that of Hey Groves and Putti (1921) based his design for the first leg lengthening device on both Lambret's and Hey Groves' work. He developed a spring-driven uniaxial fixator for the controlled distraction of the femur following Z osteotomy.

Boever (1931) devised a frame which could be built up

in size depending on the type of fracture being treated. This fixator was the direct predecessor of the Judet frame which is still in use in France (Judet, 1932). The Boever frame however did not permit closed manipulation of the fracture and it was Hoffmann (1938) who perfected the versatile external fixation frame which has become the most widely used device today (Fig 1.4). This device can be made into virtually any design depending on the particular fracture being treated and its design is such that closed manipulation is possible.

External skeletal fixation also progressed in North America where Putti's early work in leg lengthening was continued by Bosworth (1938) who reported good results in lengthening the tibiae of 24 patients, most of whom had had poliomyelitis. Interest in the external fixation of fractures was stimulated by the devices produced by Anderson (1936), Stader (1937) and Haynes (1939). Initially the reaction to these devices was very favourable. Bradford and Wilson (1942) reported that external fixation was of particular use in war surgery. They reported a very low infection rate and stated that not only did they encounter no non-union problem but on the whole fracture union was accelerated. They even suggested that under certain conditions external fixation might be recommended as routine treatment for femoral fractures.

Mazet (1943) also accepted the usefulness of external fixation but pointed out some of the problems that he had encountered with its use. He reported on nine patients who had had various complications including non-union, failure of fixation and osteomyelitis. In every case he attributed the problem to surgical errors and he pointed out the need for assiduous attention to technique if good results were to be obtained.

Shaar et al (1944) reported on the use of the Stader device in 110 consecutive acute fractures. They encountered no deep infection but did comment that they had pin seepage in 10% of the patients. There were two

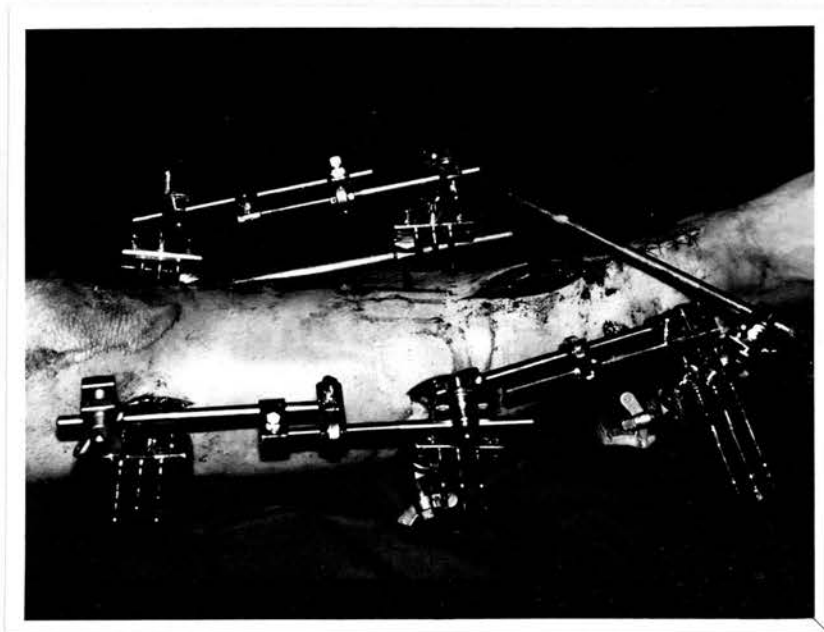


Fig 1.4

The Hoffmann external fixator being use to immobilise a compound tibial fracture. The fixator consists of a series of clamps, bars and universal joints which can be assembled into a variety of designs.

cases of ring sequestra and four cases of delayed union. They also emphasised the importance of meticulous attention to detail.

Johnson and Lyford (1944) reported on the use of the Haynes device to hold osteotomies and arthrodeses in six patients. There was one delayed union but no other significant complications although the device was kept in position for up to six months.

It is interesting that despite there being no reports in the literature of significant complications following external skeletal fixation its popularity in North America waned suddenly in the early 1950's. Johnston and Stovald (1950) published the results of a study undertaken by the Committee on Fractures and Traumatic Surgery of the American Academy of Orthopaedic Surgeons. This Committee sent a questionnaire to 3082 Orthopaedic Surgeons asking for their views on external skeletal fixation. Only 21% of the surgeons replied and of these only 27.34% felt that external fixation had a serious role in fracture management. Interestingly the surgeons who criticised external fixation were mainly those with little experience in its use whereas the experienced surgeons were more enthusiastic. The Committee felt that external fixation had no part to play in routine fracture management.

This decision, taken despite several favourable reports, and based on a grossly inadequate survey seriously slowed the evolution of fracture surgery in North America. The concept of external fixation was not reintroduced until the 1970's.

In Europe however external fixation continued to be widely practised. Both the Hoffmann and Judet devices were further modified with considerable experience being obtained particularly with the former device. The work of Lindahl (1962), Burney and Bourgois (1965), Vidal (1970) and Adrey (1970) not only helped to identify the role of external fixation but also to rekindle interest in North America.

In the last fifteen years there has been an explosion in both external fixator numbers and designs with much of the recent work being done in North America and Great Britain where there has been a particular interest in unilateral external fixation.

This recent interest in external fixation has evolved along two main pathways. The devices have either pursued a course of increasing complexity in an attempt to make one device cater for all orthopaedic problems or they have become simpler with a return to designs similar to that of Lambotte.

The modern complex devices such as the Kronner quadrilateral frame (Donald and Seligson, 1982) and the AO fixator (Muller et al, 1970) are clearly based on the Hoffmann principle and design but improved engineering and materials have resulted in their widespread use. This is particularly true of the AO device which has gained considerable popularity in Europe and North America. The main advantage of these complex devices is their inherent versatility in dealing with many orthopaedic problems but they suffer from being expensive and being relatively difficult to apply. Their main drawback however is the restricted soft tissue access which a large frame provides. This problem is at its most extreme with the circular devices such as the Kronner circular frame and the Volkov-Oganesyan device (Oganesyan, 1982) where soft tissue access is virtually denied. The hemi-circular Ace-Fischer device (Fischer, 1983) combines stability with improved soft tissue access.

Other devices have concentrated on providing fracture stability with maximum soft tissue access since the principle indication for using external skeletal fixation is in the treatment of severe compound fractures where adequate access to the soft tissues is essential. Single bar designs have the advantage that they can be applied to the subcutaneous border of the tibia without any muscle penetration. The simplest designs use bone cement to secure the transfixion pins to the external frame.

This idea was introduced by Inoue et al (1972) and Aron (1976) although Edge and Denham (1981) have documented the clinical use of this type of device. Their earliest design had no provision for compression or distraction although this facility was added at a later date. The Hughes fixator (formerly called the Sukhtian-Hughes, Sukhtian and Hughes, 1979) and the Oxford frame (Kenwright et al, 1979) are both more sophisticated unilateral devices with greater versatility and the Hughes particularly has been used in a wide range of clinical situations. The interest in leg lengthening has been maintained by the invention of the Wagner frame (Wagner, 1971) designed specifically for this function although it has also been used successfully for fracture treatment.

In addition to good soft tissue access these simpler devices tend to be cheaper and easier to apply than the more complex frames. They have however been criticised for providing inadequate fracture fixation.

Unilaterality is of course possible with the complex devices and it is of interest that Burney (1979) and Behrens (1982) now use unilateral forms of the Hoffmann and AO fixators respectively.

Several bilateral or rectangular frames have been developed. The Charnley clamp (Charnley 1953) is essentially an external fixation frame used principally for the stabilisation of arthrodeses. This design seems to have been developed from the Hey Groves double transfixion appliance and it in turn has provided the basic idea for the design of the Rezaian (Rezaian, 1971) and Day (Freeman et al, 1983) frames. The former frame is rarely used but the latter device seems to combine cheapness and ease of handling with the facility for permitting closed reduction.

Despite the number of different designs external fixators can be applied in only six basic ways although the complex fixators can be built up into virtually any design. Table 1.1 lists the possible forms of external

<u>Description</u>	<u>Applicable devices</u>	
Unilateral	Hughes	Denham
	Oxford	Hoffmann
	AO	Wagner
	Anderson	Utrecht
	Judet	Inoue
Bilateral	Day	Hoffmann
	AO	Charnley
	Rezaian	
Triangular	AO	Hoffmann
Quadrilateral	AO	Hoffmann
	Kronner	
Circular	Volkov-Oganesyan	
	Kronner	
Hemi-circular	Ace-Fischer	

Table 1.1

The six basic forms of external fixation frames and the commoner fixators that can be made into those forms.

fixators and the commonly used devices.

The large number of different devices and configurations of application seems to vindicate Keetley's view that there could be an almost unlimited number of external fixators. The situation is not helped by the fact that little work has been done on the biomechanical or clinical aspects of fracture healing with most of these frames and that descriptions of the use of many of them are anecdotal.

SECTION 1

CHAPTER 2

The Hughes External Fixation Device.
Its Design and Application.

The Hughes external fixation frame consists of two aluminium alloy bars crossed and grooved on two surfaces. Each bar is 14.3cm x 2.5cm x 1.3cm in size and is divided into eleven fixation units separated by grooves 2mm wide and 1.5mm deep (Fig. 2.1). The fixation units are crossed by multiple small grooves running at 45 degrees to the main grooves and each has a centrally placed threaded screw hole 5mm in diameter (Fig. 2.2).

The two aluminium bars are connected by two stainless steel threaded rods 8mm in diameter. A turnbuckle at the end of one of the rods enables compression or distraction to be applied to a fracture. The maximum possible bar separation is 2.7cm. Once the required compression or distraction has been applied the turnbuckle can be locked by a cap screw 5mm from the end of one of the bars.

Threaded self-tapping titanium pins are used to transfix the bone (Fig 2.3). Each pin is 4.8mm in diameter and 15cm in length. The threaded portion is 3.2cm in length. These transfixion pins are secured to the external frame by means of aluminium alloy blocks of which there are two designs.

If movement in the coronal plane is required without movement in the sagittal plane then block A can be used (Fig. 2.3). This is an aluminium alloy block 3.8cm x 2.5cm x 0.95cm in size which has three equally spaced unthreaded holes within it. One side of the block is grooved in a similar manner to the surfaces of the frame although the larger grooves are absent. These blocks are secured to the frame with 2.4cm cap screws.

When movement in the sagittal plane is required then block B (Fig 2.3) should be used. This measures 3.7cm x 2.6cm x 0.95cm on one surface but the opposite surface has been cut away and is only 1.3cm in width. There are two unthreaded holes at the ends of the block with a centrally placed circular depression within which are four peripherally located ellipsoid depressions. The two laterally placed ellipsoid depressions together with the 45 degree slope of the side walls allow movement in the

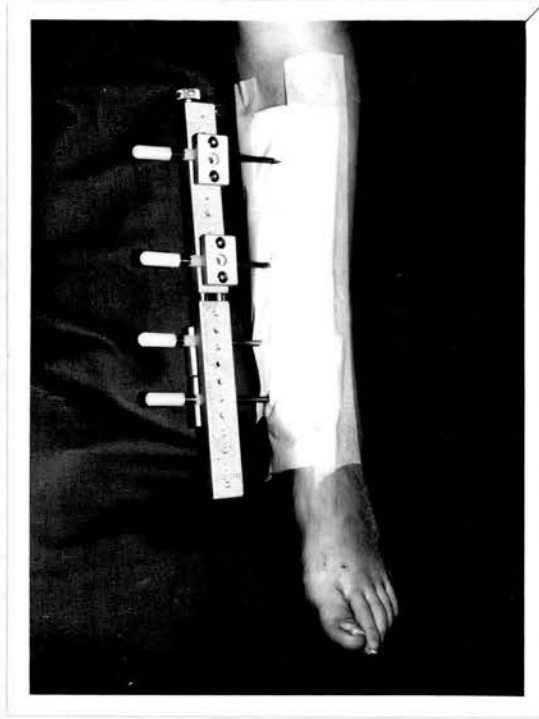


Fig 2.1

The Hughes external fixator immobilising a compound tibial fracture. The option of using both sides of the fixator bar is clearly shown.

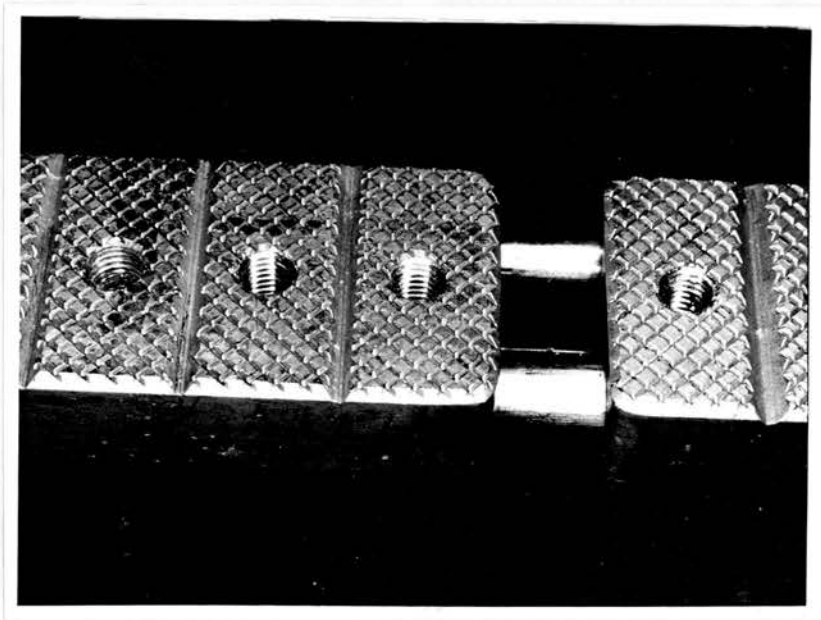


Fig 2.2

A close up view of the central part of the Hughes frame showing the individual fixation units with the larger separating grooves and the smaller grooves running at 45 degrees to the edge of the bar. The two rods that permit compression and distraction are shown.

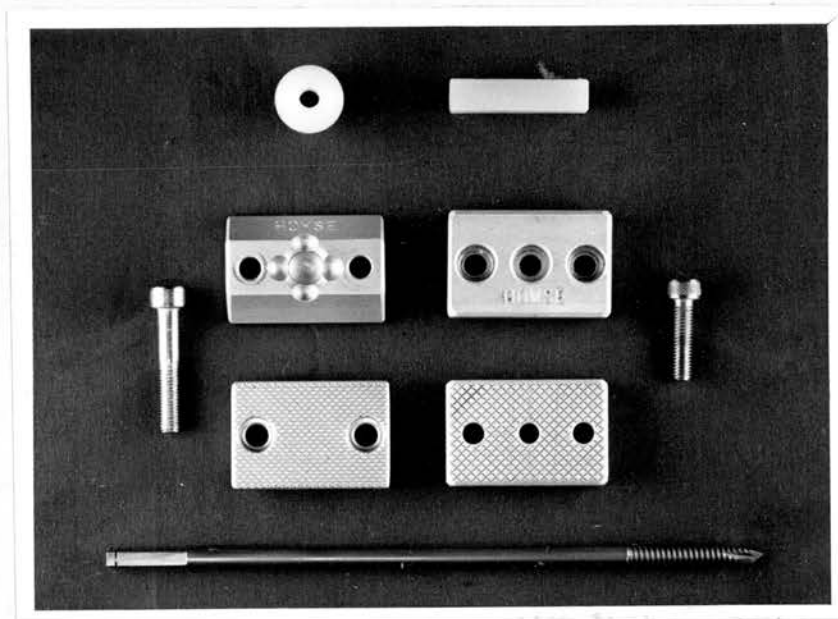


Fig 2.3

The titanium transfixion pins, two designs of aluminium alloy block with their corresponding cap screws and the two types of plastic bush available for use with the Hughes fixator.

sagittal plane. The larger of the two main surfaces of block B retains the multiple small grooves but has 25% more grooves per square cm than either the bar or block A. Block B is held to the bar by 3.4cm cap screws, the increased length being necessary to accommodate the spherical plastic bush which is required to permit movement in the sagittal plane.

Both block designs permit pin fixation without an intervening plastic bush with the larger grooves on the frame facilitating pin fixation at 90 degrees to the frame. If the pin is angled then the smaller grooves aid secure fixation. However two plastic bushes are provided to facilitate fixation and to allow for pin angulation (Fig 2.3).

If movement in the coronal plane is required there is a rectangular 3.2cm x 0.7cm x 0.7cm plastic bush available but if movement in the sagittal plane is needed then a spherical plastic bush 1.5cm in diameter must be used in conjunction with block B.

Variation in application of the frame.

Despite there being eleven fixation units on each aluminium bar the relative dimensions of the bars and the blocks ensure that only three transfixion pins can be used on each side of a fracture. These pins can be placed between 1.25cm and 13cm from the fracture site if the fracture site is aligned with the centre of the frame. In clinical use the innermost pin can usually be placed about 3cm from the fracture site. It is possible to place two pins under one block 1.25cm apart but this is usually impractical and the smallest practical distance between two pins is 2.5cm with each pin under a different block. If three pins are used with the innermost pin 3cm and the outermost pin 13cm from the inner end of the bar then the middle pin can be placed

between 6.25 and 9.25cm from this point.

Pin angulation will increase the range of potential pin placement. If the spherical bush is used or the pin is used without a bush then the theoretical potential arc of pin angulation is 140 degrees. If the rectangular bush is used the arc is reduced to 120 degrees. It is however obvious that the effective pin angulation is much less and depends on several factors such as the relative number and position of the pins as well as the distance between the bars of the frame.

If the innermost pin is placed 3cm from the fracture site and at 90 degrees to the bone then the total effective arc of angulation of an outer pin entering the bone 13cm from the fracture is approximately 50 degrees. This pin may converge at an angle of up to 5 degrees before it is blocked by a cap screw or it may diverge at an angle of up to 45 degrees before it is stopped by the inner pin (Fig 2.4). Any convergent angulation of the inner pin will reduce the divergent angulation of the outer pin.

The total effective arc of angulation of an inner pin placed at 3cm from the fracture with the outer pin at 13cm is about 60 degrees with 15 degrees of divergence being possible before the inner pin on the other bar is encountered (Fig 2.5). Again 45 degrees of convergence is possible before the outer pin stops increased pin angulation. The divergent angle of the inner pin will vary with the distance between the bars and the position of the inner pin on the other bar.

If a third pin is added to the system midway between the inner and outer pins at 3 and 13cm respectively from the fracture then its total effective arc of angulation is about 30 degrees (Fig 2.6) with 15 degrees of convergence and divergence. Any movement of this pin in the 3cm range that has already been specified will change the relative convergent and divergent angles but will maintain the total arc at 30 degrees.

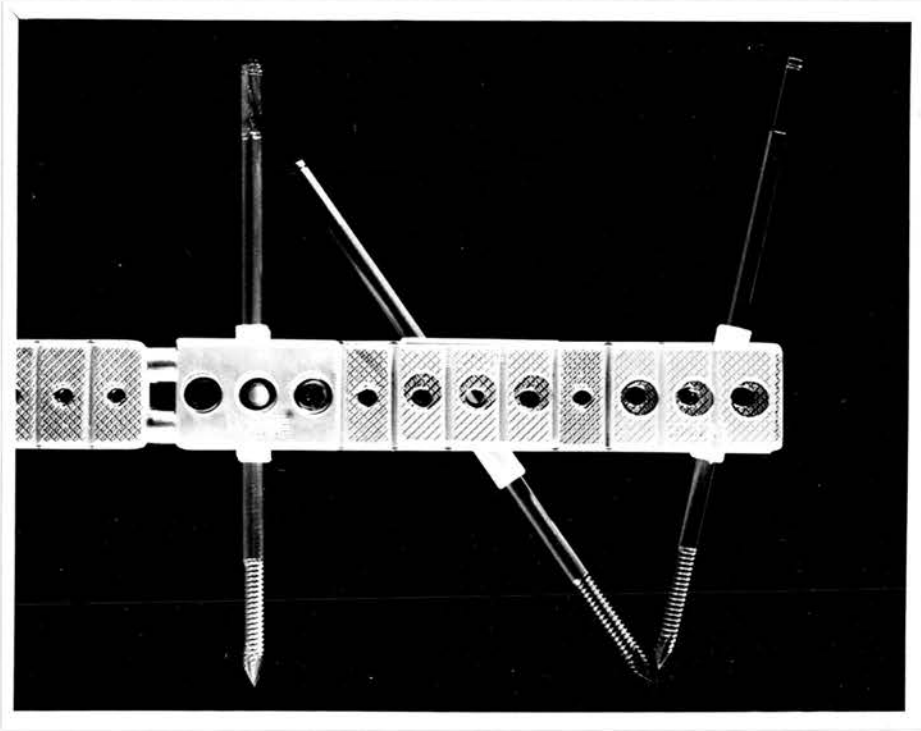


Fig 2.4

A superimposed photograph illustrating the possible range of angulation of an outer pin set at 13cm from the fracture. The range is approximately 5 degrees of convergence to 45 degrees of divergence if the inner pin is at 90 degrees to the bar and 3cm from the fracture.

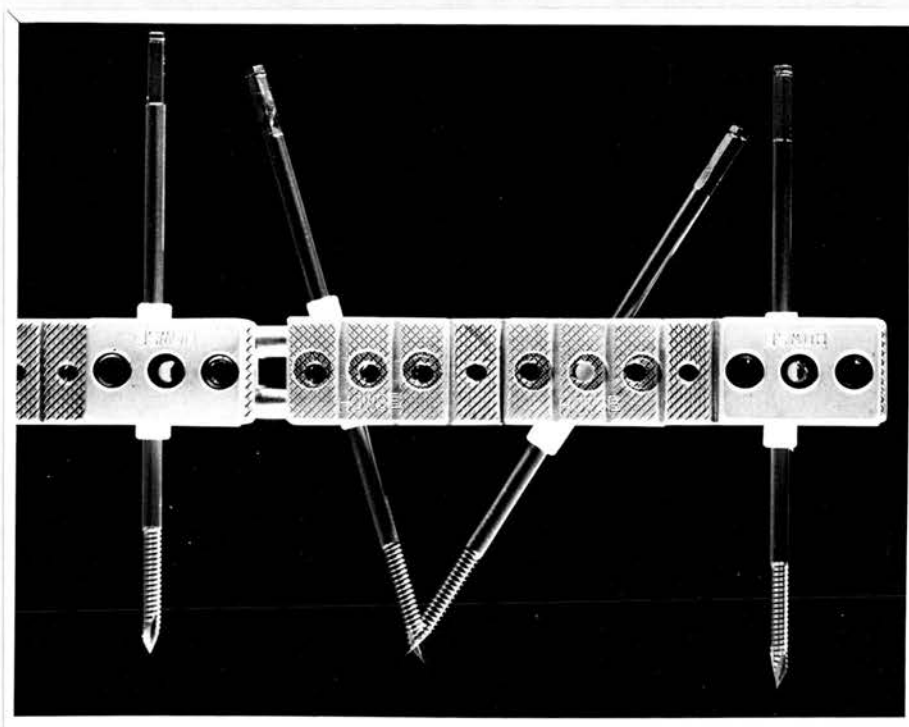


Fig 2.5

A superimposed photograph illustrating the possible range of angulation of an inner pin set at 3cm from the fracture. The range is approximately 45 degrees of convergence to 15 degrees of divergence if the outer pin is at 90 degrees to the bar and 13cm from the fracture and the other inner pin is similarly angled 3cm from the fracture.

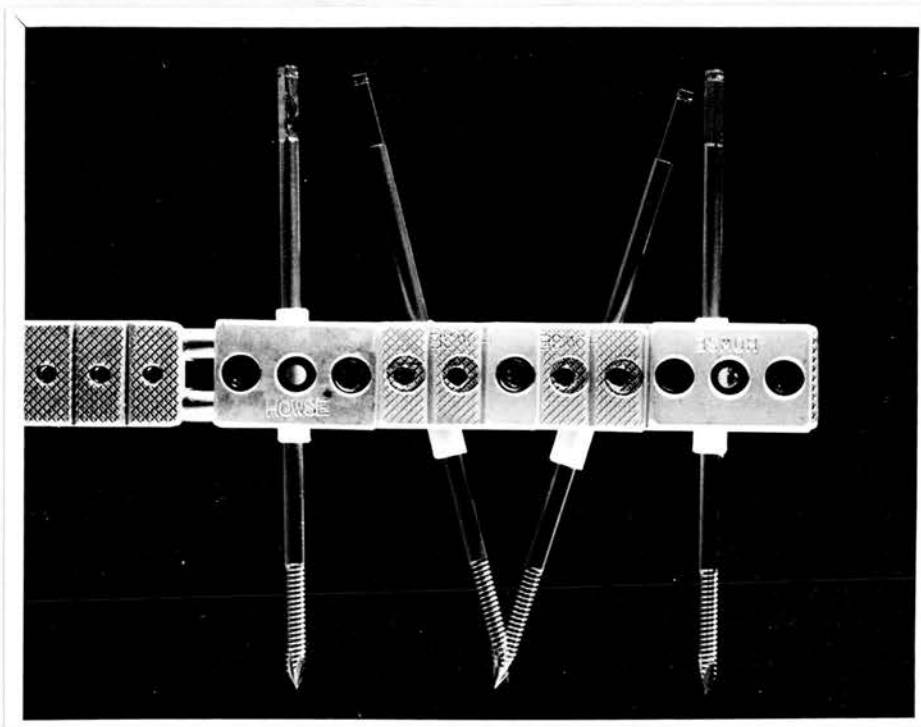


Fig 2.6

A superimposed photograph illustrating the possible range of angulation of a third pin introduced between inner and outer pins set at 3 and 13cm from the fracture. The total range is approximately 30 degrees with 15 degrees of movement being possible in each direction.

SECTION 1

CHAPTER 3

A Review of the Current Concepts of
the Biomechanical Properties of
External Fixation Devices.

The earliest studies of the biomechanics of external fixation devices were carried out in the 1960's although previous workers had recognised that with external fixation fractures could be immobilised with varying degrees of stability. Many of the early fixators were of small size and could only be applied in one particular configuration. However the advent of more sophisticated devices such as the Hoffmann meant that the particular mode of configuration of the device could influence both fracture stability and union.

Lindahl (1962) and Burney and Bourgois (1965) published the initial work on the biomechanics of the Hoffmann device. They compared the relative stiffness of fracture immobilisation achieved with a unilateral Hoffmann configuration with the other forms of fracture management existing at that time. Lindahl compared a unilateral Hoffmann frame of low stiffness with Sherman plates, staples, Kuntscher nails, screws, osteosutures and cerclages to see which device best held an oblique diaphyseal fracture. He showed that the unilateral Hoffmann did not provide rigid fracture fixation.

Adrey (1970) and Vidal (1970) both continued the biomechanical assessment of the Hoffmann device. Adrey attached strain gauges to the Hoffmann and showed that a four bar configuration was a particularly rigid configuration. Vidal however conclusively showed that the double frame configuration of the Hoffmann provided greater stiffness (Fig. 3.1). This configuration is known as the Hoffmann-Vidal double frame and has become the yardstick by which other fixators are measured.

Both Adrey's and Vidal's work was based on the assumption that the optimal fixator configuration was that which provided the most rigid fracture fixation. This was based not only on the belief that soft tissue healing would be facilitated by rigid immobilisation but also on the work of the AO group who had proposed that accurate reduction of a fracture under conditions of rigid fixation facilitated primary bone union without

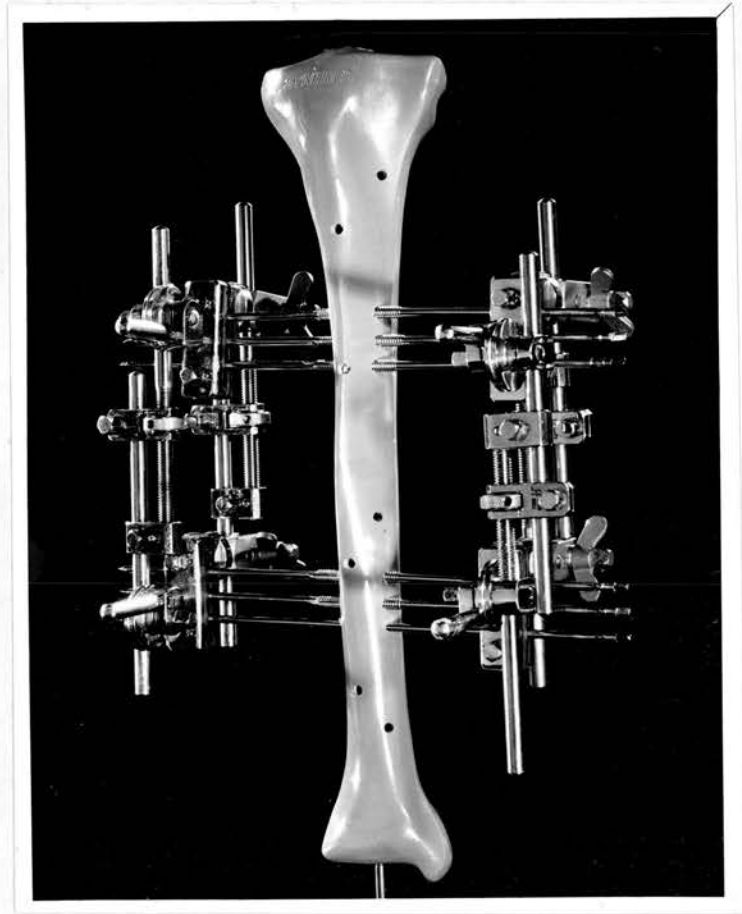


Fig 3.1

The Hoffmann-Vidal double frame. This configuration is the stiffest routinely used arrangement of the Hoffmann fixator.

callus formation and that this was advantageous. However this belief was not uniformly held and Burney continued his work with the unilateral Hoffmann frame. He made his configuration progressively less rigid (Fig. 3.2) until he arrived at his concept of elastic external fixation (Burney, 1979). Using this principle he claims to combine the advantages of external fixation with the advantages of having callus at a fracture.

Jorgensen (1972) summarised the problems regarding analysis of the Hoffmann frame when he pointed out that an almost limitless number of configurations could be made, each with its own biomechanical characteristics. He stressed that the performance of the device varied with its configuration of application and showed that the exact configuration should be defined when assessing its biomechanical properties.

Chao et al (1979) working within the framework of Vidal's earlier research looked further at the biomechanical characteristics of the Hoffmann-Vidal double frame. They rationalised the application of the device by examining its stiffness using different sizes, numbers and relative positions of the transfixion pins. The effect of altering the position of the side clamps was also examined. They examined the five static loading modes of compression, distraction, antero-posterior bend, lateral bend and torsion and computed an overall stiffness index which they referred to as the equivalent stiffness index. Using this index they compared the stiffnesses of different configurations of the device.

They showed that the Hoffmann-Vidal double frame was stiffest in compression and distraction modes and markedly weak in antero-posterior bending and torsional modes. Increasing the pin number and pin diameter increased the stiffness but increasing the side clamp separation caused a decrease in stiffness. Lastly they indicated that the transfixion pin structure was considerably weaker than the frame itself.

Fischer et al (1980) enlarged on Chao's work by

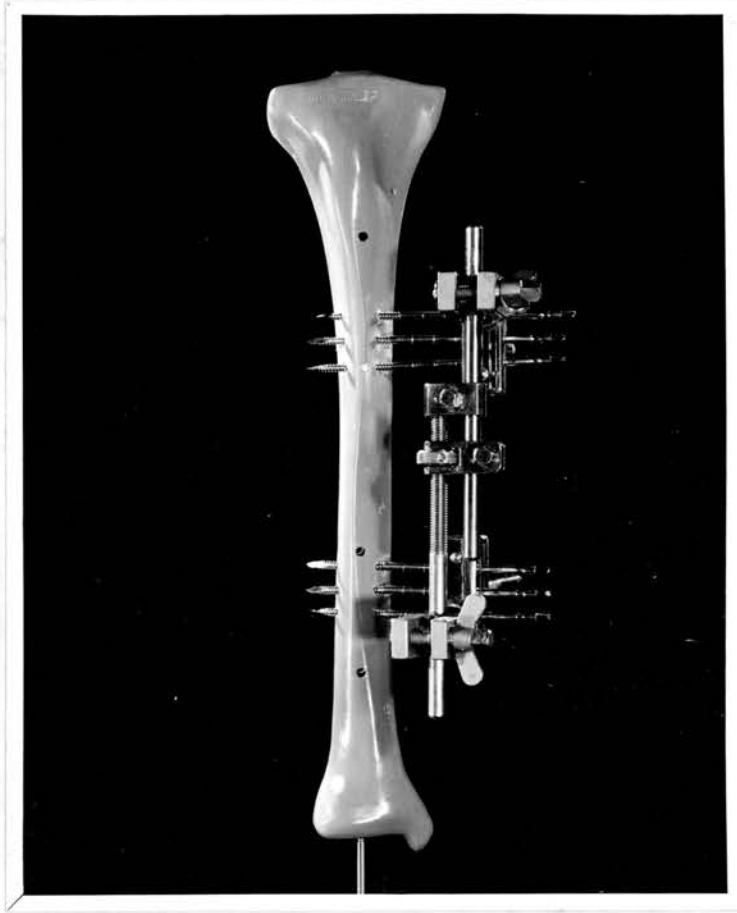


Fig 3.2

A commonly used unilateral configuration of the Hoffmann fixator consisting of two groups of three half-pins joined by a compression bar. This arrangement has been popularised by Burney.

comparing the full and half-frame configurations of the Hoffmann under the same biomechanical conditions of equivalent pin number, length, spacing and size. They found that there was a considerable loss in axial stiffness and antero-posterior bending stiffness in addition to a 50% drop in lateral bending stiffness and torsion.

Burney et al (1982) have also examined the biomechanical characteristics of the half frame or unilateral Hoffmann. They concluded that for maximum stiffness the connecting rods should be short and parallel. The clamps should be close to the bone and there should be three pins in each clamp. They stated that the unilateral form is capable of both rigid and elastic fixation although Fischer's work does not support this contention. Unfortunately Burney becomes confused with his wish to have low stiffness or elastic external fixation because it promotes callus and his biomechanical desire to promote stiffness in his fixator. His main contribution is the definition of how the unilateral Hoffmann might best be applied.

Despite its obvious importance very little biomechanical research has been undertaken on devices other than the Hoffmann. Boltze (1978) examined the AO fixator and calculated the relative stiffness of different configurations of the device. He, like Jorgensen, pointed out the need for precise definition of each configuration.

The AO device was also investigated by Campbell and Kempson (1980) who examined the relative stiffness of ten of the different configurations which might be used in clinical practice. They subjected the configurations to four loading modes and showed clearly that the most rigid form of the AO frame incorporated a rectangular system with three pins on each side of the fracture as well as an anterior bar and two cross links.

Evans et al (1979) carried out a biomechanical analysis of a pure unilateral frame in active clinical

use. They studied the Oxford device looking particularly at its resistance to compressive and bending loads. They were able to demonstrate that the system was stiffest when pins of adequate diameter were inserted so that the threaded portion was below the surface of the bone. They stated that the pins should be as far apart as possible and that the bone-fixator distance should be small. The method of clamping the pins to the bar was also felt to be important.

Haaman et al (1979) examined another single bar system, the Utrecht fixator. They measured its resistance to loading in three directions and concluded that the device was approximately biomechanically comparable to the Hoffmann-Vidal frame.

Comparisons of different external fixation devices have been performed but these are all handicapped by the need for standardisation of dissimilar equipment if valid comparisons are to be made. The easiest way to compare fixators is to assess which configurations of the devices give the highest stiffness values when loaded in different directions and then compare these stiffness values. This has been done by McCoy et al (1980) who looked at the Hoffmann-Vidal frame, two configurations of both the Anderson and Kronner devices and the Volkov-Oganesyan fixator. It would appear that these devices were chosen because approximately equivalent configurations could be set up and tested. They showed that the Kronner device was stiffest with the Volkov-Oganesyan being the least stiff.

Campbell and Kempson (1980), in addition to comparing different AO configurations, also compared the AO device with the Hoffmann-Vidal frame and the Day, Hughes, Oxford and Denham devices. The authors made the mistake of standardising pin length and location and then assuming that this would give comparable results. This is plainly not the case and the results for this part of their work are therefore inaccurate. With regard to the Hughes device they showed it to be stiffer in lateral bending

that in antero-posterior bending. They did not test its response to medial bending or shear loading.

Seligson et al (1981) set up an apparatus to compare different external fixators. They used extensimeters to measure fracture gap motion. These workers looked at shear forces and noted that double frame arrangements were stiffer than single frame devices. They stated that the Hoffmann-Vidal frame and the Wagner device were comparable in their resistance to shear forces.

Johnson and Fischer (1983) compared the Ace-Fischer hemicircular frame with the Hoffmann-Vidal double frame and showed that while the Ace-Fischer frame was stiffer in compression and antero-posterior bending modes it was less stiff in medial and lateral bending and torsional modes.

With the exception of the Hoffmann, AO, Oxford and Ace-Fischer devices very little work has been done on the biomechanical characteristics of external fixation frames. It is important to fully understand each frame that is in current clinical use.

SECTION 1

CHAPTER 4

The Biomechanical Characteristics of
the Hughes External Fixator.

An analysis of the biomechanical characteristics of the Hughes external fixator was undertaken using 45mm square beech as a bone substitute. A jig was erected using two 20cm beech blocks to represent a tibia with a mid diaphyseal transverse fracture (Fig. 4.1). The upper beech block was rigidly secured to a strengthened back plate by two 9mm bolts situated 3.5cm and 12cm from the proximal end of the upper block. The two blocks were then connected by a laterally placed Hughes external fixator so that the whole jig represented the lateral external fixation of a tibial fracture, this being a common clinical situation.

Known loads were then applied, in pre-determined modes, to the lower block and any movement permitted by the fixator was measured by an appropriately placed clock gauge sensitive to 0.001mm.

Selection of bone substitute material

Extensive use has been made of bone substitutes in this type of work because of the lack of uniformity of results when working with human cadaveric bone. Chao et al (1979) and McCoy et al (1980) both used synthetic bone made from Swedish body putty while Haarman et al (1979) used perspex rods and Johnson and Fischer (1983) used laminated linen to substitute for the human bone. Campbell and Kempson (1980) braised their fixator pins onto metal rods to provide uniform experimental conditions. Evans et al (1979) found that the load deflection curves for bone and hardwood were very similar except that those for bone showed more scatter than those for wood. They recommended that 45mm square beech was a good bone substitute and it has been used throughout this experiment.

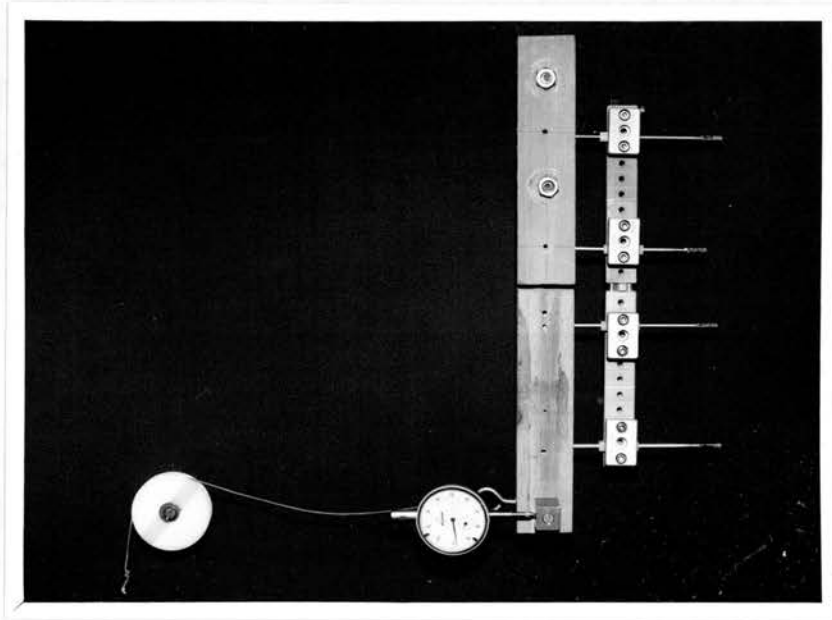


Fig 4.1

The jig used for the biomechanical experiment. The bone is simulated with two 45mm square beech blocks 20cm in length. This arrangement represents a medially applied bending load with a laterally placed fixator. Increasing loads are applied 2.5cm from the distal end of the lower block and any movement permitted by the fixator recorded on the clock gauge.

Directional loading modes

Bone is subject to five separate loading modes namely tension, compression, bending, shear and torsion (Frankel and Nordin, 1980). In the clinical situation different bones are subject to certain predominant loading modes and frequently fail under these modes. Vertebral bodies, for example, frequently fail in compression whereas the base of the fifth metatarsal fails in tension. The femoral condyles and tibial plateau are subject mainly to shear forces but the tibial diaphysis is often subject to bending forces which cause it to fail.

The lower block of the jig was therefore subjected to the following loads.

A) Tension.

The symmetrical form of the jig means that the fixator will react identically to compressive and tensile loading if the applied loads are small as in this experiment. This was demonstrated by Chao et al (1979) using the symmetrical Hoffmann-Vidal double frame. Compression was therefore not measured. Tension was measured by applying an increasing downward force to the lower block and measuring the movement permitted by the fixator with the clock gauge situated at the centre of the distal face of the lower block (Fig 4.2a).

B) Bending loads.

As the fixator is a unilateral device the effect of medial and lateral bending loads will be different whereas the effect of an anterior and posterior bending

load will be the same. Thus medial, lateral and an antero-posterior (A-P) load were assessed.

These loads were applied to a point 2.5cm from the distal end of the lower block (Fig. 4.2b). Movement was measured with the clock gauge also at 2.5 cm from the distal end of the lower block but situated forward of the centrally applied force. The A-P force was applied in the same manner but with the whole jig turned through 90 degrees.

C) Shear loads.

As with the bending forces the effect of shear loading should be measured in medial, lateral and A-P directions. The forces were applied at central points 2.5 cm from the upper and lower surfaces of the lower block. The clock gauge was positioned in the exact centre of the lower block (Fig. 4.2c).

D) Torsional loading.

The resistance to torsional loading was examined by applying the increasing force to the lower surface of the lower block. This was done by rigidly attaching a low friction pulley system to the bottom of the block such that the angle of the applied force was 45 degrees to the A-P axis. The clock gauge was placed at 90 degrees to the angle of pull. A rod, rigidly fixed to the back plate, which penetrated the exact centre of the polyethylene pulley wheel prevented movement in other directions (Fig. 4.2d).

As compressive force was not measured a total of eight different loading modes were examined. These were:-

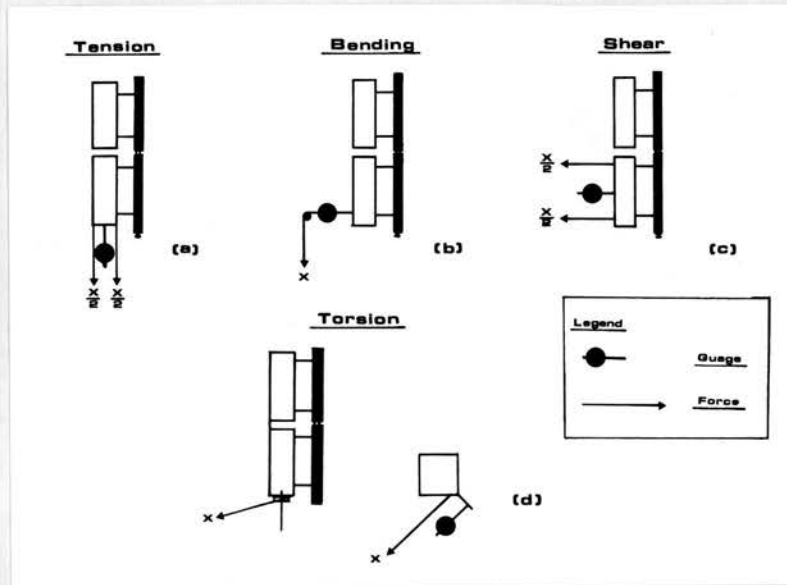


Fig 4.2

Diagrams illustrating how the different forces were applied to the jig.

- A) Tension. The gauge is centrally located on the bottom face of the block. Increasing loads are applied on each side of the gauge.
- B) Bending. Illustrated in Fig 4.1. Increasing loads are applied to the lower end of the lower block. The gauge is located forward of the load in the same plane.
- C) Shear. Gauge centrally located on block with forces applied 2.5 cm from upper and lower ends.
- D) Torsion. Side and plan views. Force is applied at 45° to block through a nylon wheel on lower block face. Gauge parallel to force in contact with a metal plate on the side of the lower block.

- 1) Medial bend.
- 2) Lateral bend.
- 3) A-P bend.
- 4) Medial shear.
- 5) Lateral shear.
- 6) A-P shear.
- 7) Tension.
- 8) Torsion.

Calculation of stiffness

The stiffness of each configuration of the Hughes fixator was calculated by graphing the relationship between the applied load and the clock gauge deflection. Ten consecutive readings of the deflection were made at each 0.5Kg increment in the applied load and the mean of these results was calculated. The resulting six means were then graphed against the applied load. It was found that if care was taken in resetting the clock gauge the results were consistently reproducible. A sample set of data for one configuration is shown in Table 4.0.

It was established that there was a linear relationship between the deflection on the gauge and the applied load. This made the calculation of a stiffness value straightforward and values were calculated for each configuration in each loading mode.

Chao et al (1979) suggested a method of calculating an overall stiffness index (K) to give a figure that is representative of all the incorporated individual stiffness values. The formula is based on the sum of squares formula modified by the use of a weighing factor (C_i).

Thus $K = \sqrt{\frac{\sum (C_i - S_i)^2}{n-1}}$ where S_i represents the eight different stiffness values and $C_i = S - S_i / S(n-1)$.

Using this formula the value for K is calculated giving equal weight to each loading mode regardless of

Clock gauge readings (mm)	Load (Kg)					
	0.5	1.0	1.5	2.0	2.5	3.0
1	0.301	0.603	0.908	1.214	1.519	1.824
2	0.302	0.604	0.912	1.214	1.520	1.824
3	0.303	0.605	0.912	1.215	1.520	1.824
4	0.306	0.605	0.912	1.213	1.521	1.823
5	0.303	0.604	0.907	1.212	1.523	1.823
6	0.305	0.605	0.910	1.215	1.519	1.824
7	0.303	0.606	0.910	1.215	1.521	1.822
8	0.304	0.608	0.911	1.219	1.521	1.825
9	0.300	0.605	0.910	1.216	1.518	1.825
10	0.303	0.605	0.908	1.217	1.518	1.826
Mean	0.303	0.605	0.910	1.215	1.520	1.824
SEM ($\times 10^{-4}$)	5.29	4.00	5.48	6.00	4.69	3.46

The raw data from which the stiffness value of 1.62×10^4 was calculated. This value is shown in Table 4.2 and is the value for two parallel pins placed 3 and 13cm from the fracture site with a pin length of 2cm. This configuration is under A-P shear loading. The clock gauge readings were accurate and all standard errors of the means were low.

Table 4.0

its magnitude.

Applied force.

The total applied force in all loading modes was 3.0Kgf or 29.43 Newtons. This was chosen because Braune and Fischer (1889) had shown that 28 Newtons represented the force applied by the weight of the foot and half of the lower leg. This was later borne out by Dempster (1955). Therefore the total applied force in the experiment was approximately equal to that applied to a tibial fracture performing a straight leg raise without using the muscles below the knee. The force was applied in 0.5Kgf (4.9 Newtons) increments starting at 0.5Kgf.

Variables examined.

As has already been outlined it is a feature of all external fixation systems that a large number of configurations can be constructed. It is important that these configurations are clinically relevant and that parameters not being examined are standardised. For example applying increasing compression to a fracture will progressively alter the stiffness. As it is common for compression to be applied in the clinical situation but rarely with any degree of accuracy the compression applied to each configuration was standardised at 0.5 Newton metres. The two component bars of the fixator were kept 1 cm apart with a narrow metal spacer and the wooden blocks were separated by 0.5cm. In the clinical situation it is frequently the case that both fracture ends and the fixator bars are separated by a small gap. The torque applied to the cap screws was kept constant at 3.0 Newton metres.

The variables that were examined were:-

- 1) Relative pin positions.
- 2) Effective pin length.
- 3) Pin number.
- 4) Pin angle.
- 5) Position of fixator bar.
- 6) Effect of plastic bushes.

A) Relative pin position.

In the clinical situation the fixator is frequently placed with its centre opposite the fracture with the fixator bars separated by 1 to 1.5cm. In this situation the innermost pin is usually situated about 3cm from the fracture site. Three different pin positions were looked at with the outer pin being moved progressively further from the inner pin (Table 4.1).

B) Effective pin length.

The fixator can be placed at a variable position away from the limb. To examine the effect of increasing the distance between the limb and the bar, stiffness values were computed for each different pin position with the bar 2, 4, 6 and 8cm from the limb.

Distance from fracture	
Inner pin (cm)	Outer pin (cm)
3	3
3	9
3	13

The three different pin locations that were examined. The inner pin was maintained at 3cm while the outer pin was moved progressively further away.

Table 4.1

C) Pin number

The effect of adding a third pin to each side of the bar was examined . A stiffness value was computed with the pins at 3, 9 and 13cm from the fracture.

D) Pin angle.

After evaluating the relative pin positions and the effective pin lengths the stiffest configuration of the device was found. The effect on stiffness of angling the inner and outer pins was assessed. The inner pin converged at 15, 30 and 45 degrees while the outer pin diverged at the same angles. The two pins were angled in separate experiments with the other pin being maintained at 90 degrees to the bar.

E) Position of fixator bar.

In clinical use the Hughes device is often placed on the antero-medial subcutaneous border of the tibia. It is therefore important to examine the biomechanical differences of using this location. The stiffest configuration of the Hughes was set up on the antero-medial side of the jig and the stiffness values and overall stiffness indices reassessed.

F) Effect of the plastic bushes.

The effect on the stiffness of using the two different bushes was assessed as was the effect of using no bush.

After the biomechanical characteristics of the Hughes frame had been examined a Hoffmann-Vidal double frame was set up on the jig and the same loads applied to it. Stiffness values and an overall stiffness index were computed.

Results.

The stiffness values and the overall stiffness indices for the three parallel pin positions at each of the four effective pin lengths, for a laterally placed Hughes fixator, are shown in Tables 4.2 - 4.4.

Table 4.2 illustrates the basic biomechanical characteristics of the fixator. It is particularly stiff in tension and resists medially and laterally applied loads better than antero-posterior loads. It is stiff in medial and lateral shear modes as well as in torsion and weakest in A-P shear and A-P bending modes. A comparison of the shear and bending results shows that if this unilateral configuration is applied to the lateral side of a long bone it will resist laterally applied forces slightly better than medially applied forces.

Tables 4.2 - 4.4 indicate that if the inner pin is maintained at 3cm from the fracture site then progressively moving the outer pin away from the fracture site raises the individual stiffness values in all loading modes. Fig. 4.3 shows the effect that movement of the outer pin has on the overall stiffness indices. At all pin lengths the overall stiffness indices were raised by moving the outer pin away from the fracture site. The highest value was obtained with the innermost pin at 3cm and the outer pin at 13cm from the fracture site.

The effect of changing the effective pin length for all the different pin positions is shown in Fig 4.4. In all parallel pin configurations of the fixator increasing

Load	Pin length (cm)			
	2	4	6	8
A-P shear	1.62	0.99	0.49	0.31
Medial shear	5.60	5.41	5.05	4.35
Lateral shear	5.77	5.59	5.24	4.45
A-P bend	1.42	0.72	0.41	0.25
Medial bend	2.50	2.35	2.20	2.25
Lateral bend	2.99	3.06	3.04	2.94
Tension	27.25	16.35	6.54	3.60
Torsion	4.36	3.63	3.00	2.66
Overall stiffness index (K)	2.26	1.79	1.25	1.14

Stiffness values and overall stiffness indices for two parallel pins placed 3 and 13cm from the fracture site at the four different effective pin lengths. (Stiffness values expressed as $\times 10^4$ Newtons/metre).

EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.2

Pin length (cm) Load	2	4	6	8
A-P shear	1.32	0.71	0.38	0.28
Medial shear	4.90	4.74	4.60	4.45
Lateral shear	5.01	4.88	4.74	4.60
A-P bend	0.98	0.51	0.31	0.17
Medial bend	2.22	2.13	1.98	2.05
Lateral bend	2.52	2.60	2.42	2.39
Tension	24.87	13.62	6.33	3.40
Torsion	4.02	3.11	2.92	2.55
Overall stiffness index (K)	1.99	1.52	1.15	0.96

Stiffness values and overall stiffness indices for two parallel pins placed 3 and 9cm from the fracture site at the four different effective pin lengths. (Stiffness values expressed as $\times 10^4$ Newtons/metre).

EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.3

Pin length (cm) Load	2	4	6	8
A-P shear	0.87	0.50	0.24	0.11
Medial shear	4.58	4.06	3.94	3.89
Lateral shear	4.70	4.18	4.07	4.01
A-P bend	0.67	0.29	0.19	0.13
Medial bend	1.99	1.94	1.89	1.93
Lateral bend	2.18	2.26	2.32	2.21
Tension	22.60	10.66	6.33	3.40
Torsion	3.84	2.86	2.69	2.42
Overall stiffness index (K)	1.81	1.27	1.05	0.88

Stiffness values and overall stiffness indices for two parallel pins placed 3 and 7cm from the fracture site at the four different effective pin lengths. (Stiffness values expressed as $\times 10^4$ Newtons/metre).

EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.4

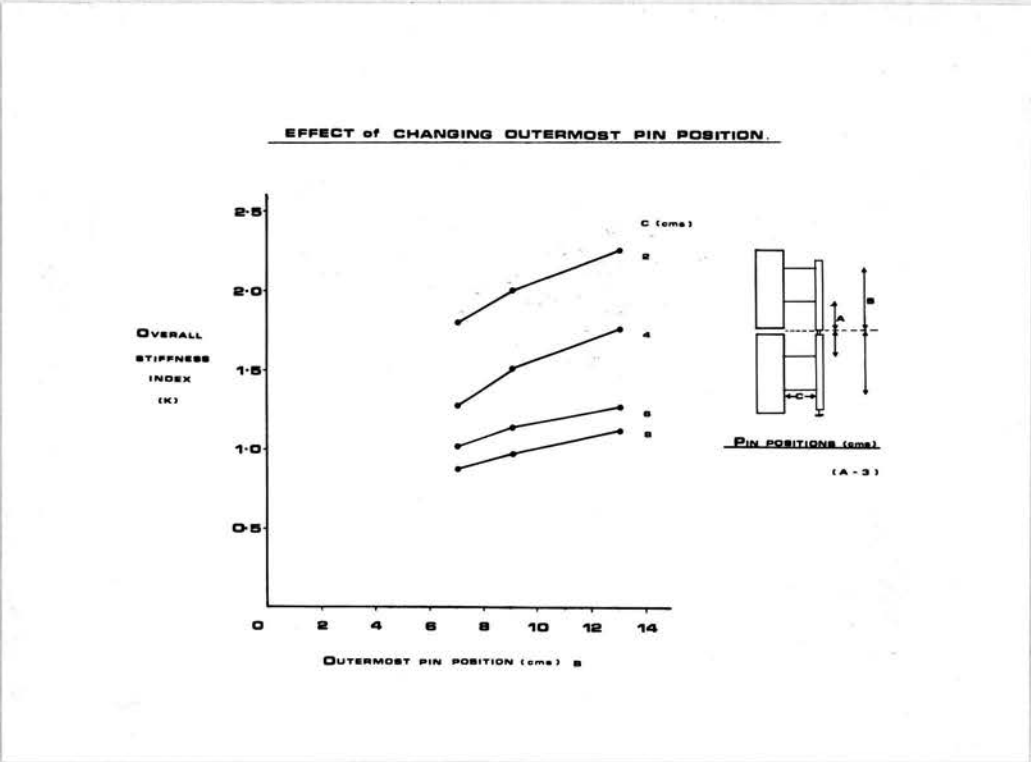


Fig 4.3

Graph illustrating the effect of changing the position of the outermost pin for each of the effective pin lengths that were used in the experiment. The overall stiffness index (K) rises as the outer pin is moved away from the fracture.

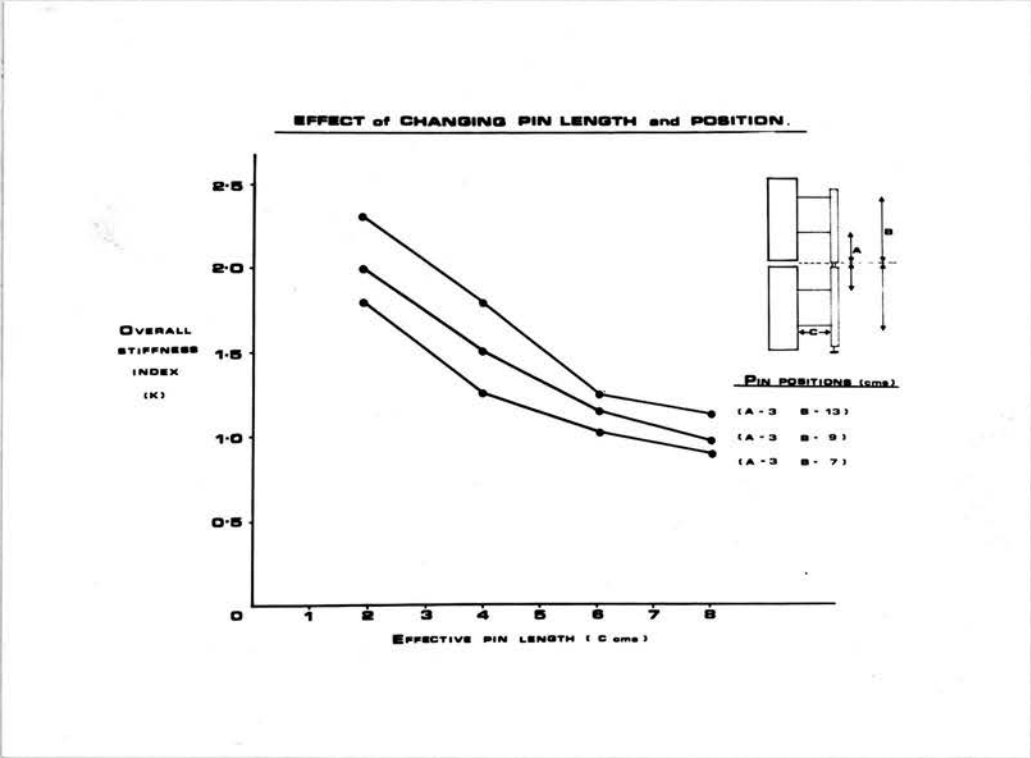


Fig 4.4

Graph illustrating the effect of altering the effective pin length for each pin position used in the experiment. The overall stiffness (K) falls as the effective pin length increases.

the effective pin length resulted in a lowering of the overall stiffness index. The highest value was obtained with an effective pin length of 2cm.

Comparison of the stiffness values in the various loading modes in Tables 4.2 - 4.4 shows that the decrease in stiffness that accompanies an increase in the effective pin length is not uniform throughout the various loading modes. A review of Table 4.2 illustrates this. Antero-posterior shear and bending loads show a marked decrease in stiffness with an increased effective pin length whereas the medially and laterally directed loads show a much smaller relative drop in stiffness. Antero-posterior shear and bending loads drop to 19% and 17.6% of their initial value when the effective pin length is increased from 2 to 8cm. In contrast medial and lateral bend drop to 90% and 98.3% respectively. The effect on tension and torsion of increasing the pin length is also different. The stiffness value for tension at a pin length of 8cm is only 13.2% of the value at 2cm whereas the equivalent figure for torsion is 61%.

The effect on the stiffness values in the various loading modes of increasing the distance between the outer pin and the fracture site is also not uniform. Again A-P shear and bending modes show the greatest drop. Moving the outer pin from 13 to 7cm causes the stiffness values in these modes to drop to 53.7% and 43.2% of the original values respectively. None of the other loading modes exhibit the same drop in stiffness value, all being maintained between 73% and 88.1%.

It is of interest that increasing the effective pin length with a lateral bending load results in an initial increase in stiffness followed by a decrease.

Increasing the pin number to three pins on each side of the fracture does not result in a significant change in any of the stiffness values or in the overall stiffness. Table 4.5 shows the effect of adding a third pin 10cm from the fracture site between the 3 and 13cm pins.

Load	Total pin number	
	Four	Six
A-P shear	1.62	1.64
Medial shear	5.60	5.52
Lateral shear	5.77	5.76
A-P bend	1.42	1.40
Medial bend	2.50	2.57
Lateral bend	2.99	3.18
Tension	27.25	27.24
Torsion	4.36	4.35
Overall stiffness index (K)	2.26	2.26

Stiffness values and overall stiffness indices for four and six parallel pins situated at 3/13 and 3/10/13cm from the fracture site. The effective pin length is 2cm. (Stiffness values expressed as $\times 10^4$ Newtons/metre). EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.5

Load	Pin angle (degrees)			
	0	15	30	45
A-P shear	1.62	1.59	1.68	1.59
Medial shear	5.60	5.45	5.38	5.30
Lateral shear	5.77	5.97	5.97	5.24
A-P bend	1.42	1.40	0.90	0.72
Medial bend	2.50	2.48	2.43	2.34
Lateral bend	2.99	3.32	3.06	2.76
Tension	27.25	24.82	23.01	19.13
Torsion	4.36	4.86	4.22	4.12
Overall stiffness index (K)	2.26	2.14	2.18	1.89

Stiffness values and overall stiffness indices for a configuration with the pins 3 and 13cm from the fracture. The effective pin length is 2cm. Variation of stiffness with increasing divergence of the outer pin is shown. (Stiffness values expressed as $\times 10^4$ Newtons/metre). EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.6

Load	Pin angle (degrees)			
	0	15	30	45
A-P shear	1.62	1.54	1.72	1.55
Medial shear	5.60	5.68	5.77	5.35
Lateral shear	5.77	5.85	5.94	5.39
A-P bend	1.42	1.38	0.84	0.38
Medial bend	2.50	2.81	2.46	2.19
Lateral bend	2.99	3.21	2.89	2.62
Tension	27.25	24.50	22.29	18.86
Torsion	4.36	5.45	4.30	4.15
Overall stiffness index (K)	2.26	2.27	2.10	1.87

Stiffness values and overall stiffness indices for a configuration with the pins 3 and 13cm from the fracture. The effective pin length is 2cm. Variation of stiffness with increasing convergence of the inner pin is shown. (Stiffness values expressed as $\times 10^4$ Newtons/metre). EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.7

Pin length (cm) Load	2	4	6	8
A-P shear	4.36	2.45	1.61	1.01
Medial shear	3.58	2.06	0.98	0.53
Lateral shear	2.30	1.40	0.74	0.47
A-P bend	2.33	1.53	0.77	0.62
Medial bend	1.70	0.92	0.48	0.37
Lateral bend	1.53	0.88	0.52	0.32
Tension	22.30	10.51	4.45	2.97
Torsion	5.11	4.30	3.89	3.67
Overall stiffness index (K)	1.96	1.12	0.64	0.48

Stiffness values and overall stiffness indices for a parallel pin configuration with the pins 3 and 13cm from the fracture. The bar has been placed antero-medially and the stiffness values for the different effective pin lengths are shown. (Stiffness values expressed as $\times 10^4$ Newtons/metre). EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.8

Changing the angles of the inner and outer pins in the stiffest of the four pin configurations (effective pin length 2cm and the pins situated at 3 and 13cm) did alter the stiffness values and the overall stiffness indices. The effect of progressively diverging the outer pin from the parallel position to 45 degrees is shown in Table 4.6.

It is apparent that the decrease in stiffness caused by diverging the outer pin is again not uniform throughout the loading modes. Angling the pin seems to protect A-P shear compared with A-P bend which drops to 50.7% of its original value. The overall stiffness index drops as the angle increases.

If the outer pin is placed at 90 degrees to the bar and the inner pin is placed at an increasingly convergent angle the stiffness values and overall stiffness indices change (Table 4.7).

Again A-P shear seems to be protected by angling the pins whereas the stiffness for A-P bend at 45 degrees drops to 26.7% of the value with the pins parallel. It is interesting that the overall stiffness value is raised if the inner pin converges at 15 degrees but if the angle exceeds this the value drops.

If the position of the fixator bar is changed so that it is on the antero-medial border there is a change in the stiffness values and the overall stiffness indices. Table 4.8 shows the results for parallel pin placements at 3 and 13cm.

Comparison with Table 4.2 will show that the overall stiffness indices for antero-medial placement are not only lower than for a lateral fixator placement but the values drop more quickly with increasing pin length. Placing the bar antero-medially increases the stiffness of fixation in the A-P direction with both shear and bending loads. Torsional stiffness is also increased. There is however a drop in stiffness in medially and laterally applied forces as well as in tension. The other striking feature of the antero-medially placed fixator is

the relative difference in stiffness values between the 2 and 8cm effective pin lengths. In contrast to the laterally placed fixator all the stiffness values drop to between 13.3% and 26.6% of their original values except for torsion which is maintained at 71.8%.

The effect of the plastic bushes at a specific pin position and effective pin length was examined as was the effect of not using a bush. In this case the effect of placing the transfixion pins in the grooves separating the fixation units was examined. The results are shown in Table 4.9.

For comparative purposes the Hoffmann-Vidal frame was examined. Prior to the commencement of the experiment ten different configurations of the Hoffmann were analysed on the jig and Vidal's statement that his double frame (Fig. 3.1) was the most rigid of the common configurations was confirmed. Accordingly the stiffest configuration of the Hughes was compared with the Hoffmann-Vidal double frame (Table 4.10). The Hoffmann transfixion pins were placed at 9, 11 and 13cm from the fracture and the side clamp separation was kept to a minimum.

Discussion.

The jig used in this experiment is very much simpler than those used by other workers. This is to its advantage if the results gained are reproducible and accurate. Table 4.0 shows a sample of the results from the jig indicating their reproducibility. It must be emphasized however that great care is required to achieve consistency as the clock gauge must be reset accurately after each reading.

The linear relationship found between the deflection reading and the applied load probably only exists for these relatively small loads and if much larger loads were placed on the system it is possible that the stiffness values would have to be calculated in a different manner. However the applied loads in this

Type of bush	Stiffness
Rectangular	2.50
Spherical	1.45
None	
Pin in groove	2.50
Pin out of groove	2.02

Stiffness values for the two bushes and no bush at one particular configuration. The pins were 3 and 13cm from the fracture with an effective pin length of 2cm. A medial bending load was used. (Stiffness values expressed as $\times 10^4$ Newtons/metre). EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.9

Load \ Fixator	Hughes (A-M)	Hughes (lateral)	Hoffmann (H-V Frame)
A-P shear	4.36	1.62	2.62
Medial shear	3.58	5.60	2.90
Lateral shear	2.30	5.77	3.10
A-P bend	2.33	1.42	2.16
Medial bend	1.70	2.50	2.33
Lateral bend	1.53	2.99	2.45
Tension	22.30	27.25	14.00
Torsion	5.11	4.36	5.30
Overall stiffness index (K)	1.96	2.26	1.60

Stiffness values and overall stiffness indices for parallel pin configurations with the pins 3 and 13cm from the fracture for both the laterally and antero-medially (A-M) placed Hughes fixators. Effective pin length is 2cm. The results for a comparably located Hoffmann-Vidal double frame are shown. (Stiffness values expressed as $\times 10^4$ Newtons/metre). EACH STIFFNESS VALUE IS CALCULATED FROM 10 INDIVIDUAL RESULTS.

Table 4.10

experiment were felt to be representative of the loading on a tibia through which no weight was being taken.

The main disadvantage of this jig is the difficulty involved in setting it up to achieve consistent results. It was necessary to accurately place both the loads and the gauge when changing the wooden blocks. The use of wood was advantageous in that it could be changed between experiments and gave consistent results. The obvious criticism of its use is that loosening of the pin/wood interface is unlikely to resemble pin/bone loosening. The results gained on this jig therefore apply to a clinical situation where pin/bone loosening has not occurred. The same criticism can be levelled at other jigs which use a bone substitute material.

Given these criticisms it is now possible to define which configuration of the Hughes fixator will hold a fracture most rigidly.

1) The effective pin length should be 2cm. It is difficult in the clinical situation to place a bar exactly at a particular pin length. The bar should be placed as close to the limb as is practical.

This close proximity of the bar to the limb has also been suggested by Evans et al (1979) using the Oxford device and alluded to by Chao et al (1979) who placed the side clamps of the Hoffmann at 7.5cm to accommodate the size of a thigh.

2) With the inner pins at 3cm from the fracture the outer pins should be placed at 13cm. Again it may well be impossible to achieve this in the clinical situation. For maximum stability the inner pins should be as close to the fracture as possible with the outer pins as far away as is practical.

The effect of pin separation has mainly been studied in the Hoffmann where a group of three pins of smaller diameter are used instead of the larger diameter pin used with the Hughes. Both Chao et al (1979) and McCoy (1980)

found that the altering the distance between the pin groups did affect stiffness although not markedly in torsion. McCoy also found that changing the distance between the fracture and the inner pin groups had less effect on stiffness. Eghker (1980) laid down comprehensive guidelines for using the Hoffmann in particular fractures and suggested that the strength of the bone into which the pin was inserted was more important than the pin separation. Tables 4.2 - 4.4 show that with the Hughes fixator an increasing pin separation affects A-P shear and bending modes more than the others. Torsion, tension and medial and lateral shear are maintained at greater than 80% of their original value.

3) The inner pins should converge at 15 degrees. This again caused a reduction in stiffness in A-P shear and bending modes as well as in tension although the stiffness values for the other modes were increased. The slight increase in the overall stiffness index gained by angling the pins is not enough to outweigh the advantage of applying the fixator with all pins at 90 degrees to the frame. This parallel configuration allows the bar to be moved away from the leg after a period of time. The possible advantage of this will be discussed later. The only other work on pin angulation was done by Evans et al (1979) who suggested that a 20 degree divergence of the outer pins on the Oxford fixator would increase the stiffness.

4) The addition of a third pin to the system does not increase the stiffness. Clinically this is only necessary when a separate bone fragment needs to be stabilised. Chao et al (1979) suggested that the addition of more pins to a Hoffmann system did increase stability.

The effect of changing the pin diameter was not examined as it was the intention to provide biomechanical guidelines for the application of the currently available Hughes device. The use of other pins would affect the

stiffness which varies with the fourth power of the radius and the Young's modulus of the component material. The importance of pin construction will be mentioned later.

5) The rectangular bush confers greater stiffness than the spherical bush but no more than placing a transfixion pin without a bush in one of the larger grooves on the bar. Clinically no bush need be used if the pin is placed at 90 degrees to the bar but if the pin is inserted at any other angle the use of a rectangular bush will increase the stiffness. The spherical bush may of course be used to allow movement in the sagittal plane.

6) A laterally placed fixator bar confers greater overall stiffness than an antero-medially placed bar (Table 4.9). However the antero-medial location seems to provide a more even spread of stiffness values over the range of loading modes and it still has a higher overall stiffness than the Hoffmann-Vidal frame. As the antero-medial location is clinically useful in the treatment of tibial fractures the relative stiffness of the Hughes device in this location is encouraging.

Stiffness in the different loading modes.

The lack of uniform stiffness in the different loading modes (Tables 4.2 - 4.4) is important as it has been stated that different loads affect bone healing in different ways. Many workers have investigated the response of healing bones to different loads but unfortunately the choice of the load used in any one experiment seems to have been dictated by individual preference and ease of experimental use rather than by any knowledge of which loads a fracture is likely to meet

during the healing phase. Most workers (Weir et al, 1949; Henry et al, 1968; Jager et al, 1976; Sarmiento et al, 1977; Ekelund et al, 1981) have used a bending force but torsional forces (Burstein and Frankel, 1971; Braden et al, 1973; Paavolainen et al, 1979) and a tensile force (Evans, 1973) have also been used.

The situation is further complicated by work done by Ekelund et al (1981) who compared the effect of different loading modes on bone healing. They showed that healing rat femora treated without rigid fixation regained full bending strength within 8 weeks but did not regain full torsional strength for 13 weeks. It would therefore seem that healing bone may respond differently to different loads at different times in the healing process.

The exact loads to which any fractured bone will be exposed over the period of time necessary to heal the fracture are unknown. They will vary depending on which bone is fractured but with regard to the tibia it is likely that it will be exposed to all the different loading modes at different times and frequently to a combination of modes.

Lanyon et al (1975) demonstrated the complexity of the loading modes acting on the human tibia during the common physiological activities of walking and jogging. Carter (1978) using Lanyon's data showed that tibial loading during normal walking is compressive during heel strike, tensile during the stance phase and compressive during push off. A relatively high shear stress appears in the later portion of the gait cycle denoting significant torsional loading.

It is likely that the tibial loading following fracture will be different from that acting on the intact bone and will depend on several factors.

A) The type of fracture treatment.

It is known that internally fixing fractures rigidly alters the bone's response to different loads. Jager et al (1976) demonstrated a decrease of 70-80% in the bending strength of osteotomised rabbit tibiae as compared with only 40% after conservative treatment.

Braden et al (1973) reported recovery of only 36.7% of normal torsional stiffness 10 weeks after plate fixation of canine femora.

Paavolainen et al (1979) showed that the torsional strength of osteotomised rabbit tibiae following internal fixation was normal up to 9 weeks but fell between 9 and 24 weeks after the osteotomy indicating a change in the bone. This change is attributed to the phenomenon of stress sparing (Uthoff and Dubuc, 1971; Akeson et al, 1976). The possible stress sparing effect of external fixation is unproven although Terjesen and Benum (1983) have suggested that the Hoffmann-Vidal frame does have such an effect but that it is less pronounced than with a metal plate. It is highly probable that any stress sparing of external fixation is directly proportional to its stiffness. The exact effect however that external fixation might have on a healing bone's response to different loading is unknown.

B) Presence of callus.

Callus increases the area and polar moments of inertia of a healing bone. Therefore the greater the quantity of callus the greater the resistance to bending and torsional loading.

C) Weight-bearing status.

If a patient with a long bone fracture is managed by non weight-bearing mobilisation then the loading to which the fracture will be subjected will be derived mainly from muscle action. The effect of any muscle action will depend on the extent of any muscle damage or paralysis, the particular exercise regime used and whether the fracture has been rigidly fixed. If full weight bearing on a tibial fracture is allowed then the loading may approach that shown by Carter.

Radin et al (1979) reiterate the statements of previous authors in saying that excess shear and bending loads are detrimental to fracture union. Thus a good external fixation device should presumably be stiff in these modes. Lanyon's work suggests that additionally it should be stiff in torsion. However Sarmiento's work suggests it need not be stiff in tension or compression as cyclical loading seems to facilitate union.

The Hughes device fulfils some of these criteria. It is stiff in medial and lateral shear and bending modes as well as in torsion. It is however less stiff in A-P shear and bending modes and presumably excessively stiff in tension. The question as to what constitutes "correct" stiffness can only be answered by experiment or by comparison with a proven fixator.

Table 4.10 shows the comparative results for the two locations of the Hughes and the Hoffmann-Vidal frame. Comparison of the Hoffmann-Vidal with the laterally applied Hughes shows that the Hoffmann-Vidal is stiffer in A-P shear, bending and tension modes but less stiff in the other modes. The antero-medial Hughes and the Hoffmann-Vidal show a much more uniform distribution of stiffness values than the laterally applied Hughes suggesting that they may better resist all the various loads to which the healing bone may be exposed. The lower stiffness in tension seen with the Hoffmann-Vidal might

be an advantage as cyclical loading of the fracture may be facilitated.

Comparison with other devices is difficult. As previously mentioned the survey of Campbell and Kempson (1980) did not compare the stiffest configurations of the various fixators. However they did show that the Hughes device was relatively stiff in lateral bending and compression modes but they did not examine it in shear or torsional modes.

McCoy et al (1980) set up six configurations of four different fixators using a Hoffmann-Vidal frame that was similarly arranged to the one in this experiment. They did not measure shear force but found that the Hoffmann-Vidal frame was weakest in A-P bending mode and progressively stiffer in torsion, lateral bending and tension modes. Extrapolating their figures makes the Hughes device comparable in A-P bending mode with the bilateral Kronner and Roger Anderson devices and the circular Volkov-Oganesyan fixator. The only device to show a significantly higher overall stiffness was the five bar Kronner. It would seem that the Hughes fixator, whether applied to the lateral or antero-medial sides of a limb, is stiffer than the Hoffmann-Vidal double frame and comparable to other more complex devices.

Sarmiento (1977) has re-illustrated the importance of cyclical loading in facilitating fracture union. The relative stiffness of the Hughes in tension may therefore be a drawback and the Oxford fixator which is also stiff in tension (Campbell and Kempson, 1980) has been equipped with a device to provide cyclical fracture loading (Evans and Harris, 1980). Tables 4.2 - 4.4 illustrate that stiffness in tension drops markedly with an increasing pin length regardless of the pin locations. If cyclical loading is desired it can be introduced by simply moving the fixator bar away from the leg. Fig. 4.4 shows how the drop in overall stiffness varies with the effective pin length for any of the three pin locations. Interpolating this graph allows the change of stiffness

value of any change in pin length to be assessed.

SECTION 2

CHAPTER 1

A Review of the Current Concepts of
Bone Healing and Bone Blood Flow.

Some workers have claimed that external skeletal fixation promotes bone union (Parkhill, 1897; Bradford and Wilson, 1942) while others claim that it promotes delayed or non-union of fractures (Gustilo, 1982) This dichotomy of opinion makes it important to study fracture healing using external fixation under controlled conditions. The clinical studies in the literature are uncontrolled and open to criticism. A full histological survey of fracture healing with external fixation does not exist although Hey Groves (1921) made some relevant observations and Yamagishi and Yoshimura (1955) and later White et al (1977) looked at the effect that external fixation had on callus formation.

The "classical" method of fracture healing with callus formation has been extensively studied. In this process the early stages of fracture repair are marked by acute changes of local haemorrhage, inflammation and necrosis. This is followed by a proliferation of repair tissue and osteogenic cells leading to the formation of fibrous tissue, cartilage and new bone at the fracture site. After union of the fracture there follows a degree of remodelling of the callus and new bone.

This view of fracture healing persisted until Lane in 1914 wrote about the concept of bone healing without callus formation. Krompecher (1937) analysed ossification in relation to local mechanical conditions and suggested that given rigid conditions healing of cortical bone without callus could occur. Danis (1949) suggested that this was the ideal mode of healing for long bone diaphyseal fractures and this concept of primary bone union was widely taken up throughout the world principally as a result of the elegant work carried out by the AO group (Schenk and Willenegger, 1967; Perren et al, 1969; Allgower et al, 1975).

The effect of different stiffnesses of fracture fixation was examined by Yamagishi and Yoshimura (1955) who used a small bilateral external fixation frame incorporating Kirschner type wires to stabilise rabbit

tibial osteotomies. They examined the callus formed and demonstrated that the amount and its histological make-up varied with the amount of movement permitted at the fracture site. It was however Hey Groves (1921) who had initially commented that his external transfixion device had permitted healing of cat tibial osteotomies with a small amount of callus. He attributed this to "the absence of friction between the bone ends".

Fracture healing can be regarded as a spectrum with primary bone union, or healing without callus, at one end and dependence on callus to bridge fracture gaps at the other. The healing process between these extremes is modified by several factors including movement.

It is important however not to regard these two ends of the spectrum as different types of bone union. There are only two embryological methods of forming bone, by membranous and endochondral ossification. Membranous ossification involves fibroblasts increasing in size, their nuclei becoming eccentric and then changing to osteoblasts. Osseous material is then secreted and eventually trabeculae are formed. In endochondral ossification there is an invasion of a pre-existing cartilaginous model (callus) by osteoclasts and osteoblasts and gradually new bone replaces the cartilage. The importance of callus in bone healing cannot be overemphasized. It must be remembered that in evolutionary terms attempts at closed or open fracture reduction have occurred only very recently and even today many fractures will have to heal across a gap which is not bridged by bone. Cartilaginous callus has evolved as a method of bridging bone gaps and filling bone defects and its principle controlling mechanisms reflect the conditions found in displaced fractures.

The production of cartilage is affected by a number of variables such as the age of the animal and the amount of movement at the fracture site. Movement promotes chondrogenesis as well as callus proliferation probably through shearing stresses (Sevitt, 1981). The production

of cartilage is also stimulated by relative ischaemia (Ham, 1930) and is therefore affected by the amount of initial fracture displacement and the degree of soft tissue damage associated with this. A common misconception is that cartilage formation and its ossification occur consecutively. In fact the processes occur simultaneously and there is evidence that cartilage may actually stimulate ossification (Urist, 1965).

If cartilage formation is important in bridging bone gaps then endochondral ossification is important in determining the final strength of the bridging bone. In this process the swollen cartilage cells are invaded by capillaries which bring in osteoblasts to the area. Chondrolysis occurs and new bone is laid down between the ingrowing vessels. The woven bone filaments so formed coalesce to form trabeculae. Endochondral ossification is peripheral in origin but may occur in a number of places simultaneously. The cartilage mass is therefore progressively reduced in size until it disappears to be completely replaced by bone. The cartilaginous basis for this type of fracture repair is sometimes reflected by the appearance of central foci of cartilage within bony trabeculae long after clinical fracture union.

By tradition the word callus has come to mean the cartilaginous and osseous repair tissue associated with the periosteum rather than the repair tissue seen in the medulla. However with the exception of the amount of callus formed the processes are not dissimilar. The role of medullary ossification has been understated in recent literature but it is very important in the healing of human fractures. The process relies mainly on membranous ossification although islands of cartilage are often seen in the medulla which undergo endochondral ossification. Medullary ossification is obviously important in the bony union of cancellous fractures but Sevitt (1981) has suggested that it plays a major role in the early stabilisation of rigidly fixed long bone fractures.

Membranous and endochondral ossification account for

all bone healing. When bone healing with callus formation occurs membranous ossification is still seen in the medullary tissue. In primary bone union the histologically visible cutter cones form cortical channels down which membranous ossification can proceed. Different conditions merely modify the relative proportions of each component part of the healing process.

Despite our fairly extensive knowledge about bone healing there are still a number of simple questions that need to be answered.

1) What is the role of the fracture haematoma? The traditional view is that fibrin in the haematoma facilitates fibrovascular invasion which encourages healing. Allgower (1956) suggested that haematoma leucocytes may be transformed into fibroblasts. Pritchard (1963) suggested that the osteogenic blastema arising from the medulla invades the haematoma and produces new bone. Heiple and Herndon (1966) suggested that haematoma was detrimental to fracture healing. This view is supported by Sevitt (1981) who states that the haematoma is quickly lysed and implies that it has no particular function.

2) What is the clinical role of primary bone union? There is no doubt whatsoever that primary bone union occurs in the experimental situation but Sevitt (1981) has expressed doubts as to its occurrence in the clinical situation. In the few human post-mortem specimens that he examined soon after rigid plating he found gap healing by secondary means rather than primary bone union.

3) What is the relative importance of intra-medullary healing? This aspect of bone union has been neglected compared with the role of cortical healing. Charnley (1953) showed that medullary union was

facilitated by compressive rigid fixation and Sevitt has stated that stability provided by medullary union is clinically a very important part of primary bone union.

The blood supply of bone.

The blood supply of bone is also incompletely understood. Its vascularity was first noted by van Leuwenhoek in 1674 and Havers in 1691 described the penetration of the cortex by the nutrient artery and the metaphyseal arcade. Albinus in 1756, using a vascular injection technique, was able to demonstrate fine blood vessels in the Haversian canals (Rhineland and Wilson, 1982). He identified vessels entering and leaving the bone from both the periosteal and endosteal surfaces. This apparently dual vascularity was not investigated further until the 1940's when more sophisticated injection techniques facilitated research. More recently the use of radioactive tracers, microspheres and scanning agents has been introduced.

The microangiographic studies of Trueta and Harrison, (1953), Rhineland and Baragy, (1962) and Rhineland, (1972, 1974) indicate that bone does have a dual blood supply derived from the nutrient artery and the periosteum. Recent debate has centred round three main areas.

- 1) What is the proportion of the cortex supplied by the medullary and periosteal circulations?

- 2) What is the direction of blood flow in the bone?

- 3) What vascular connections exist between the two blood supplies and do modern experimental techniques affect these anastomoses?

Most authors believe that the medullary supply is the more important of the two and that it supplies about two-thirds of the cortex. This belief is supported by the work of Trueta and Cavidas (1955), Brooks and Harrison (1957), Morgan (1959) and Gotham (1961) with rabbits. Brookes (1958) confirmed similar findings in the rat as did Gotham (1961) in the Blue Mangabey monkey and Brookes (1958) and Nelson et al (1960) in the human tibia.

The flow of blood in bone is thought to be centrifugal moving from medulla to periosteum (Brookes, 1971; Rhineland, 1972, 1982). Branemark (1959) is in a minority in suggesting a centripetal flow but his experimental model had had most of the cortex removed and therefore was not physiological. Brookes (1971) has however demonstrated that under pathological conditions blood flow can become centripetal. This has been shown experimentally following ligation of the nutrient artery in a rabbit and also in human occlusive vascular disease and osteoarthritis.

The question of possible anastomoses between the two blood supplies is important as not only does it influence the cortical blood supply following fracture but it also affects the use of micro-angiographic techniques. If anastomoses exist but are usually closed then the injection of non-physiological materials under high pressure may well open them creating centrifugal flow and giving a false idea of the medullary contribution to the cortical blood supply.

De Bruyn (1970) thought that anastomoses were common and that the two blood supplies were in series. However he is in a minority. Gotham (1961) showed the presence of small anastomoses but most workers believe that if anastomoses exist they are of little functional significance and that the blood supplies are in parallel (Brookes and Harrison, 1957; Lopez-Curto et al, 1980).

Recent research has been into bone blood flow and its differences within and between bones. Various techniques

have been used to measure flow. Venous outflow measurement (Cumming , 1962; Post and Shoemaker, 1964), tracer uptake and clearance techniques (Copp and Shin, 1965; Kelly et al, 1971; McElfresh and Kelly, 1974), labelled erythrocytes (Brookes, 1971) and the fractionation of diffusible indicators (Kane and Grim, 1969) have all been used. However none of these methods permit the measurement of total or regional blood flow to one or more bones in the same animal and thus the use of labelled microspheres to measure flow has become popular (Wagner et al, 1969; Archie et al, 1973; Heymann et al, 1977).

Bone blood flow after fracture has been examined by several workers (Gothman, 1961; Rhinelander and Baragy, 1962; Cavidas and Trueta, 1965; Rhinelander et al, 1968; Paradis and Kelly, 1975; Hughes et al, 1978). After a fracture the blood supply to the bone increases (Wray and Lynch, 1959; Rhinelander, 1968). This increase has also been shown after an experimentally induced tibial osteotomy in dogs and to be at its maximum of four times the control value at 10 days after osteotomy following which it progressively decreases to return to control values at about 112 days (Paradis and Kelly, 1975).

SECTION 2

CHAPTER 2

Bone Healing and Bone Blood Flow with
the Hughes External Fixator. The
Technique and Results of an Animal
Experiment.

To investigate the effect of external skeletal fixation on bone healing and blood flow an experiment was set up using the New Zealand white rabbit as the experimental model. Bilateral tibial osteotomies were performed in ten adult male rabbits. In all animals the right-sided osteotomy was stabilised with a miniature Hughes external fixator while the contra-lateral osteotomy was treated with a long leg cast for comparative purposes. The animals were kept alive for between one and ten weeks and were then sacrificed after the injection of radioactively labelled microspheres. The activity, and hence the blood flow, was assessed at the fracture sites and bone healing examined using light microscopy. In three animals renal artery blood was sampled prior to sacrifice so that comparative values of fracture site blood flow could be calculated.

Materials and Methods.

A) External fixation device.

Prior to the commencement of the experiment it was necessary to design an external fixation device suitable for use on the rabbit tibia (Fig 6.1). This was closely modelled on the Hughes device although owing to problems of scale the two pins on each side of the fracture are secured under one clamp. It measures 7.8x 1.2x 1.2cm.

B) Operative technique.

The experimental technique was adapted from that of Lunde and Michelsen (1970). Each rabbit was anaesthetised with halothane using a barbiturate for induction. Once anaesthesia was established the abdomen and lower limbs were shaved and the skin prepared with hibitane (Fig

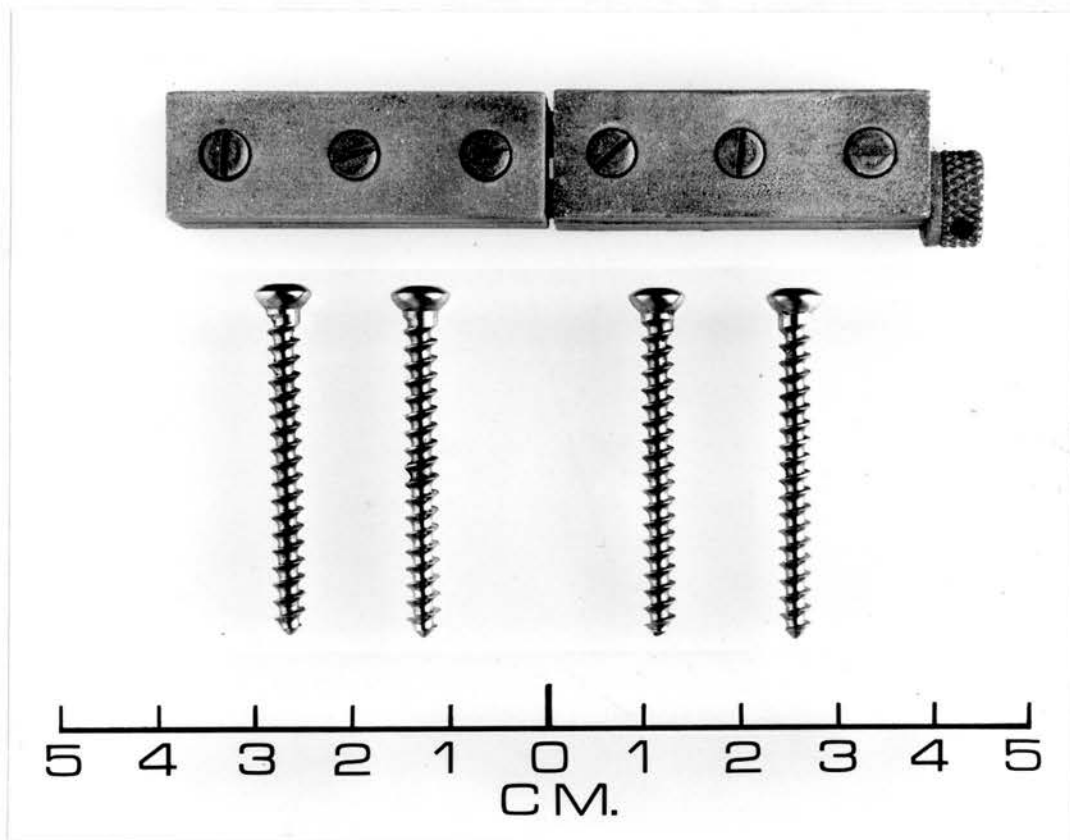


Fig 6.1

The small external fixator devised for stabilising tibial osteotomies in the rabbit. It is modelled on the Hughes device and measures 7.8 x 1.2 x 1.2cm. The AO small fragment cortical screws were used as transfixion pins with two screws being held in each half of the device.

6.2).

An incision was made on the antero-medial border of the right hind limb such that it would eventually lie at a distance from the transfixion pins (Fig. 6.3). After mobilisation of the skin, individual incisions were made down to bone to allow four transfixion pins to be inserted into the tibia. The medial border of the tibia is virtually subcutaneous and little muscle dissection is required to place the pins.

Each pin hole was pre-drilled and tapped according to standard AO techniques (Muller et al, 1979) and four 3.5mm AO cortical screws (Fig 6.1) were placed in the bone as transfixion pins. The pins were parallel and placed at 90 degrees to the bar. Both cortices of the tibiae were transfixed and each pin penetrated the skin through a separate skin incision (Fig 6.4). After insertion of the four pins a 0.4mm osteotomy was made in the mid diaphyseal area below the tibio-fibular synostosis, using a hand held blade (Fig. 6.5). The periosteum was not elevated prior to making the osteotomy. After clearing all bone debris with saline a 7.8cm Hughes fixator was then applied (Fig. 6.6) without compression. Compression was not applied for two reasons. It is difficult to standardise the amount of compression that can be applied in both the experimental and clinical situations. In addition many of the fractures that are treated with an external fixator are very comminuted and the application of compression is neither possible nor desirable. After application of the fixator the wound was closed and post-operatively a light cast was applied over the fixator to minimise rabbit interference with the wound and the device.

A skin incision was then made on the antero-medial border of the left hind limb and a similar osteotomy made in the tibia. The wound was closed and a standard long leg cast was applied (Fig. 6.7). A post-operative X-ray was taken (Fig. 6.8).

As each operation was performed under clean rather



Fig 6.2

A New Zealand white rabbit shaved and prepared for surgery. Sterile drapes are used and the feet are wrapped in sterile bandages.



Fig 6.3

The incision is made on the antero-medial aspect of the limb such that it will lie forward of the transfixion pins after closure.

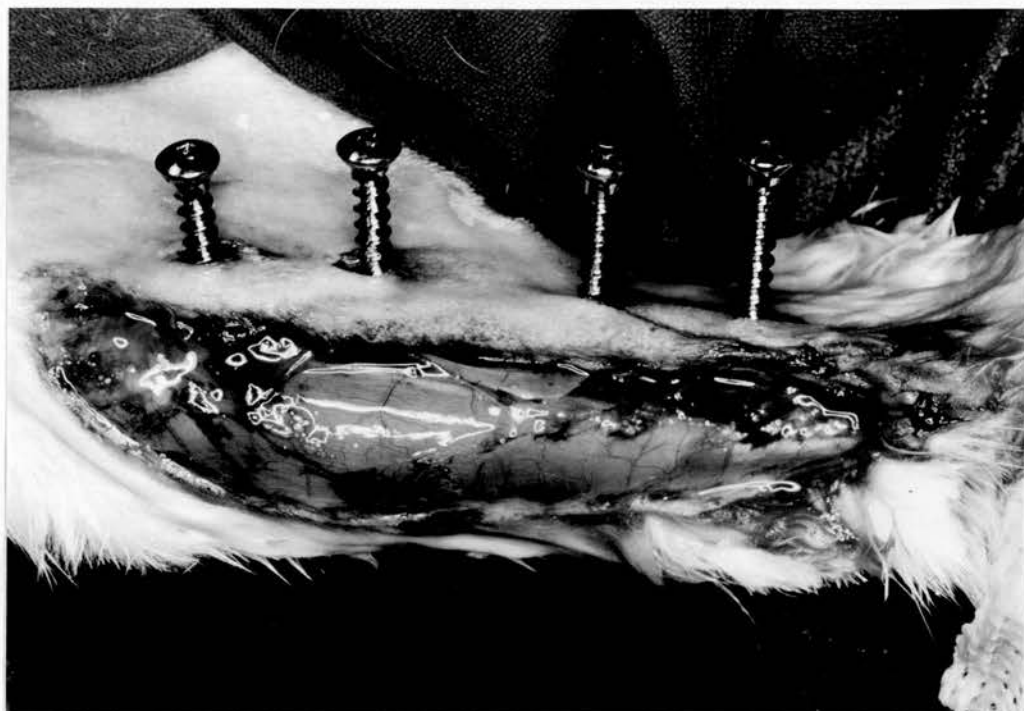


Fig 6.4

AO small fragment cortical screws were used as transfixion pins. They were inserted parallel to each other and at right-angles to the bone. Each screw was inserted through a separate skin incision with as little muscle dissection as possible being performed.



Fig 6.5

A mid-diaphyseal osteotomy was performed with a hand held, \emptyset .4mm saw. Power was not used because of the possible damage to bone and soft tissue.

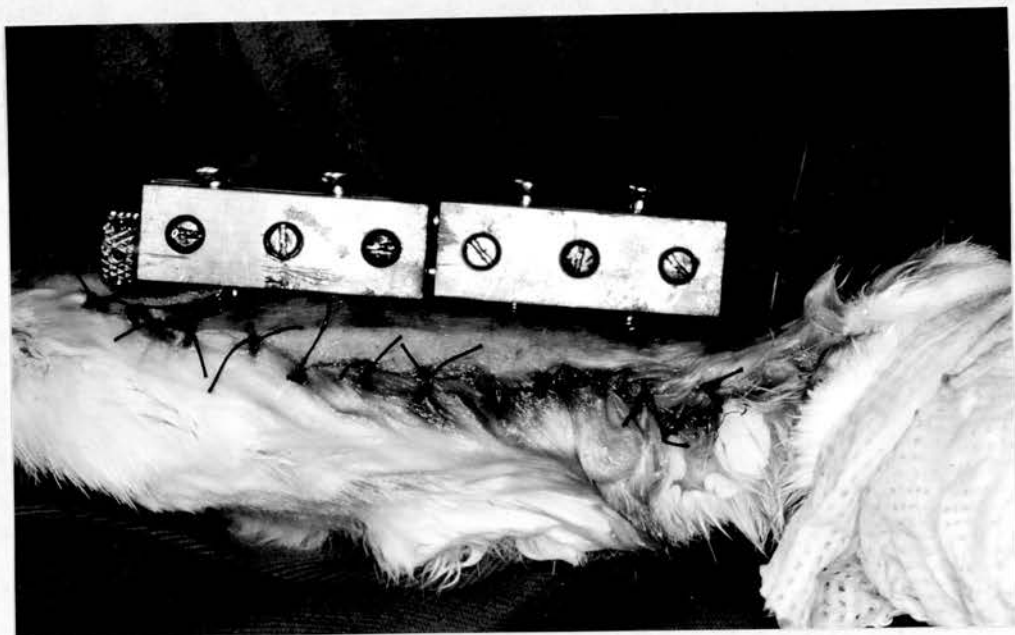


Fig 6.6

The rabbit external fixator was then applied and the component screws tightened. Compression was not applied. The wound was then closed with non-absorbable sutures.



Fig 6.7

After a similar osteotomy was made in the contra-lateral tibia bilateral baycast casts were applied. On the left side a standard long-leg cast was used to control the osteotomy while on the right a light cast was applied over the fixator to minimise animal interference with the device and the skin incision.

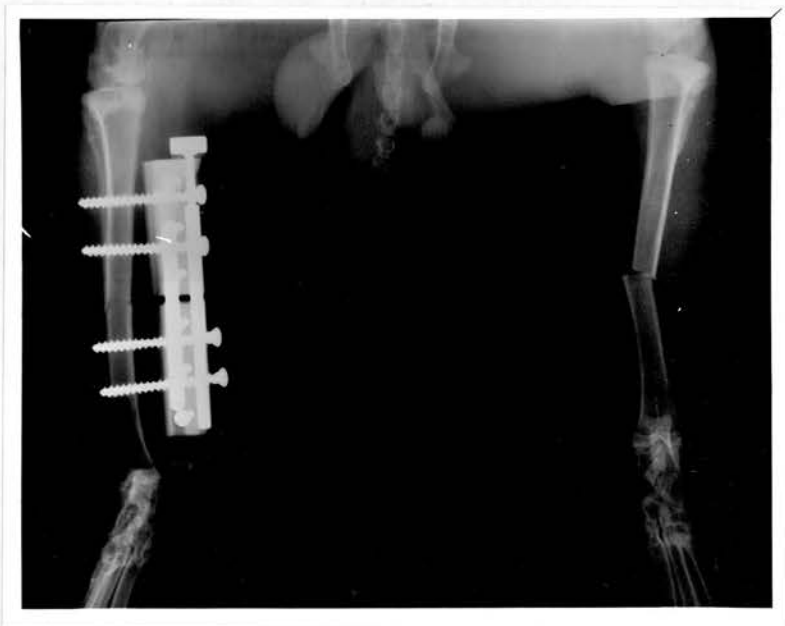


Fig 6.8

A post-operative X-ray showing the positions of both osteotomies.

than sterile conditions a prophylactic intra-muscular dose of 200mg of cephaloridine was given pre-operatively and repeated four and eight hours post-operatively. Oral antibiotics were then continued for a further month.

After an interval of between one and ten weeks the animals were again anaesthetised and on this occasion the left brachial artery was exposed in the axilla. It was cannulated with the tip of the cannula being passed into the aorta (Fig. 6.9) and approximately 10^6 15μ Cobalt⁵⁷ labelled microspheres were introduced using a slow injection technique and the artery flushed with saline. After one minute the animal was killed with an intravenous barbiturate.

To provide information on absolute flow rates the left renal artery of three rabbits was cannulated prior to sacrifice. After the microspheres had been evenly distributed through the circulation and before sacrifice a known quantity of blood was sampled from the renal artery in a known time and its activity counted. Calculation of this reference flow allowed flow measurements at the fracture sites to be calculated from the formula.

$$F_b = F_r \times \frac{C_b}{C_r}$$

where F_b = unknown blood flow.

F_r = renal artery blood flow in ml/min/g.

C_b = counts / min / g bone.

C_r = counts / min / g renal artery blood.

After sacrifice the tibiae were removed (Fig. 6.10) and sectioned into three with the paired middle thirds containing the fracture sites and an approximately equivalent amount of bone including all callus. The activity in all bone sections was then counted.



Fig 6.9

At the second operation the brachial artery was isolated in the left axilla and cannulated. Approximately 10^6 15μ Cobalt⁵⁷ labelled microspheres were then injected into the aorta just above the left atrium. The animal was sacrificed one minute later.

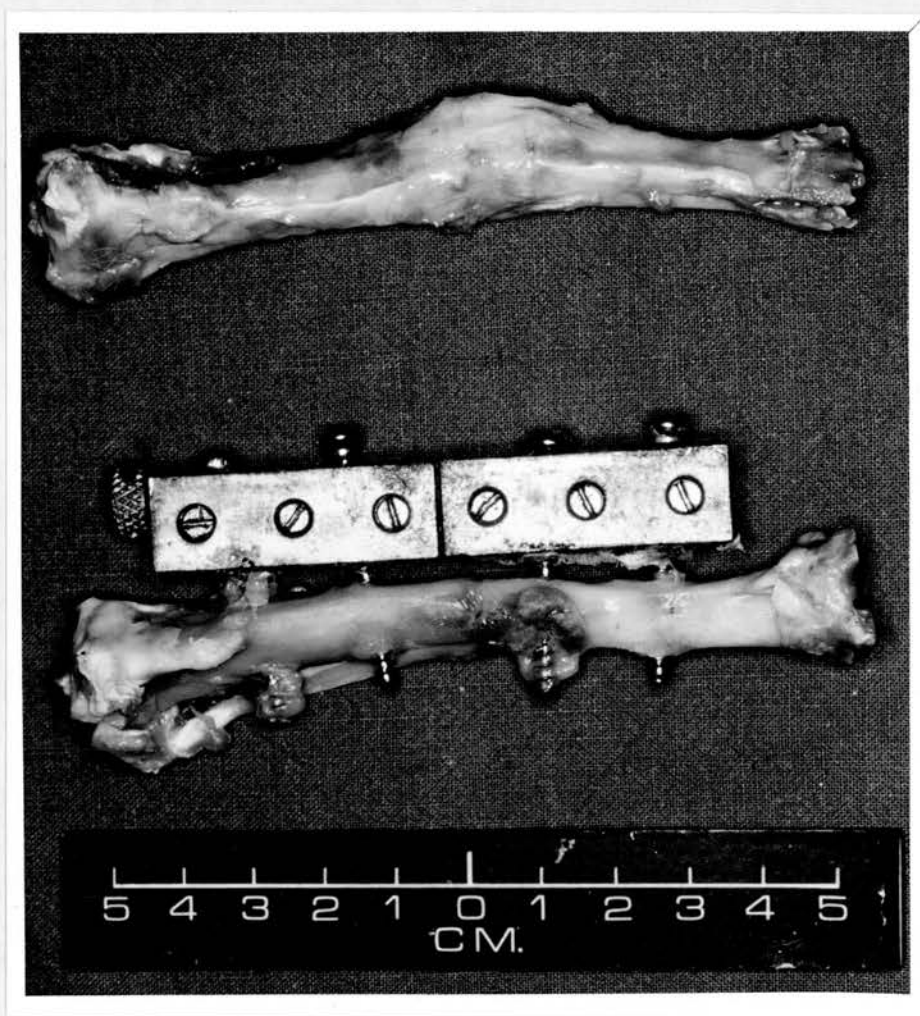


Fig 6.10

After sacrifice the soft tissue was removed prior to the tibiae being sectioned and counted. Note the difference in callus formation between the externally fixed and the control fractures. These fractures are 8 weeks old.

C) Choice of experimental animal.

Adult male New Zealand white rabbits were used as the experimental animal. Young rabbits were not used because of the possible effect of the open epiphyses on blood flow. All animals were between 3.5 and 4.0 Kg in weight and had been successfully quarantined prior to the experiment suggesting that they were all in good health.

Sevitt (1981) has pointed out the difference in bone healing between small animals and man stressing particularly that the relative sizes of the bones and cortices are different and that this alters healing. However many workers (Trueta and Cavadias, 1955; Brookes and Harrison, 1957 and Gothman, 1961) have demonstrated that rabbits show very similar bone healing to man and Rahn et al (1971) have clearly demonstrated that primary bone union occurs in the rabbit.

The rabbit is particularly suitable for this type of experiment as detail of the tibio-fibular diaphyseal blood supply is known (Brookes and Harrison, 1957 and Gothman, 1961). Furthermore Gothman has shown that the tibial nutrient artery passes laterally down the leg to enter the diaphysis at the level of the tibio-fibular synostosis. Therefore osteotomies made below this level will not damage the nutrient artery.

Several workers have demonstrated the mechanical symmetry of paired rabbit bones (Currey, 1969; White et al, 1974) and as Paradis and Kelly (1975) and Hughes et al (1978) have shown that mineral deposition in bone and bone blood supply are closely related it seems reasonable to assume that paired rabbit tibiae have a similar blood flow. Morris and Kelly (1980) have shown this to be true for the dog but in view of the importance of this point to the final results the distribution of ^{57}Co labelled microspheres in the intact paired rabbit tibiae was investigated. Two rabbits were injected and it was found that the activity between the legs varied by less than 2%.

The only disadvantage of using the rabbit is that the fixator must be placed medially as a lateral location not only risks damage to the nutrient artery but also demands considerable muscle dissection. As tibial fixators in man are frequently placed antero-medially this was not considered a major problem.

D) Bone blood flow assessment.

The bone blood flow was estimated using 15 μ Cobalt⁵⁷ labelled microspheres. The technique of injecting microspheres was first used by Ya et al (1961). They injected 60 μ microspheres in an attempt to get chemotherapeutic agents into small blood vessels. The technique has been successfully used for the estimation of blood flow by several workers (Lunde and Michelsen, 1970; Marcus et al 1976; Morris and Kelly, 1980).

The principle behind the use of labelled microspheres to estimate bone blood flow is that microspheres will become trapped in blood vessels of the appropriate diameter. The numbers of trapped microspheres will be directly proportional to the number of patent blood vessels and therefore the level of activity recorded from the microspheres will vary directly with the blood flow.

Gross et al (1981) reviewed the use of labelled microspheres and concluded that if certain criteria were met they provide a valid method of estimating blood flow. They suggested that the microspheres should be 15 μ in size and that they should be injected slowly into the left atrium to ensure good arterial mixing. The amount of microsphere suspension fluid should be kept to a minimum and the artery should be flushed with saline after injection. These criteria were met in this experiment.

The major disadvantage of using microspheres in animals is that they will not detect transient changes in blood flow occurring over a few seconds. As this experiment seeks to measure gradual flow changes this disadvantage is not a problem.

If the results are to be valid then all the microspheres must be removed in one pass through the circulation. This was shown to occur before the commencement of the experiment by injecting microspheres into the left brachial artery of two rabbits and then sampling the blood from the right brachial artery after the microspheres had distributed themselves in the circulation. This sampled blood showed no activity beyond that obtained from the background.

E) Choice of casting material

All casts were made of Baycast, a modern resin based waterproof material. This was found to be impervious to urine and too hard to be chewed by the rabbit.

Results.

The differences in bone weight and activity between the externally fixed and the cast-treated leg are seen in Table 6.1. Comparison of the relative weights of the tibiae shows that the cast-treated tibiae are heavier than the externally fixed bones. This is due to the difference in the amounts of callus produced at the fracture site (Fig. 6.10).

Table 6.1 also shows the weight and microsphere counts per gram of bone of each tibial fracture site. With the exception of weeks two to four comparison of the relative activities at the fracture sites always shows greater activity in the cast-treated leg. Thus the last column in Table 6.1 shows the percentage increase in activity of the cast-treated fracture compared with the externally fixed fracture. The values for weeks two to four are expressed as a percentage decrease.

The results are shown in graphical form in Fig. 6.11 where the graph line represents the percentage change in



Time (wk)	Tibial weight (gm)		Fracture site weight (gm)		Fracture site activity *(cts/min/gm)		%Diff
	EF	CT	EF	CT	EF	CT	
1	11.9	13.6	2.89	3.73	151	187	+23.7
2	10.9	11.6	2.37	2.77	117	114	-2.6
3	10.8	11.6	2.57	3.07	110	108	-1.8
4	15.6	16.9	8.80	10.10	601	595	-1.0
5	12.7	16.2	4.61	8.40	286	315	+10.1
6	11.2	12.2	4.10	5.50	264	378	+43.2
7	14.8	17.2	3.68	4.75	420	656	+56.2
8	15.1	16.5	4.82	5.83	1391	2507	+80.2
9	13.2	14.7	3.44	5.93	1397	2581	+84.8
10	15.7	17.1	6.20	6.40	965	1836	+90.3

Relative weights of paired tibiae and fracture sites and relative fracture site activities. The percentage difference in activity in the cast-treated fracture compared with the externally fixed fracture is shown in the last column. (EF = Externally fixed, CT = Cast-treated).

* Counts per minute per gram of bone

Table 6.1

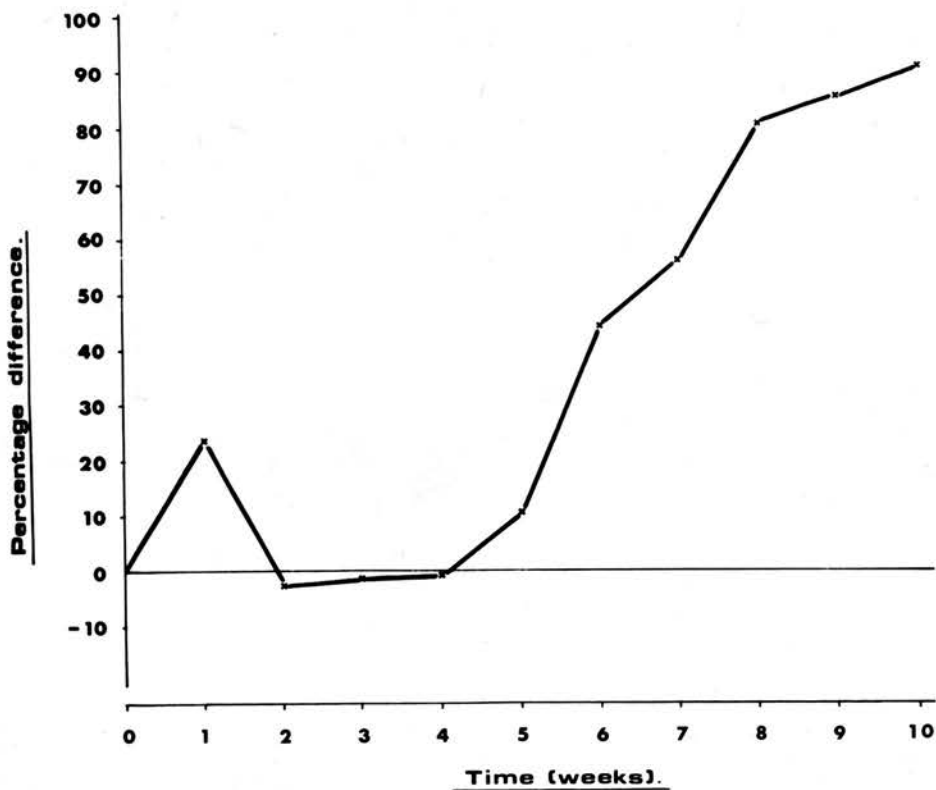


Fig 6.11

A graph showing the percentage difference in activity in the cast-treated tibia compared with the externally fixed tibia over the 10 week period. The important difference occurs after 4 weeks when activity in the cast-treated tibia (the graph line) greatly exceeds that of the fixed tibia.

activity in the cast-treated fracture compared with the externally fixed fracture. This shows that there is a small increase in activity in the cast-treated fracture site at week one followed by a period of three weeks of very similar activity at both fracture sites. At the fifth week however there is a difference in the relative activity at the cast-treated fracture site with a progressive rise up to week ten where there is a 90.3% difference in activity, and therefore blood flow, between the two fracture sites. The graph starts to level off at the eighth week suggesting that the percentage difference may not increase much further.

The fracture site blood flow was quantified at weeks one, four and seven. The results are shown in Table 6.2.

The reasons for the flow differences between the two fracture sites become apparent when the histology of the healing fractures is examined sequentially. The fracture sites at week one show considerable differences. In addition to the bony overlap seen in the cast-treated fracture (Fig. 6.12) the obvious differences are the relative rates of medullary osteogenesis and the amount of periosteal callus that has been formed. The cast-treated fracture has a considerable quantity of haematoma and inflammatory exudate between the bone ends. There is early periosteal callus but no sign of any medullary osteogenesis. In contrast the externally fixed fracture (Fig 6.13) shows little haemorrhage or inflammatory exudate but the early signs of medullary osteogenesis are already present with the deposition of fibro-vascular tissue in the medulla. There is very little periosteal callus formation but early periosteal membranous ossification can be seen in both fractures.

By three weeks the differences are even more apparent. In the cast-treated fracture (Fig. 6.14) most of the haematoma has been resorbed and the early signs of medullary osteogenesis now exist. There has been a considerable periosteal response with the formation of a large amount of cartilaginous callus much of which has

Time (wk)	Blood flow (ml/min/gm tissue)	
	Fixed fracture	Cast-treated fracture
1	0.028	0.035
4	0.099	0.109
7	0.141	0.270

Values for fracture site blood flow at weeks one, four and seven.

Table 6.2

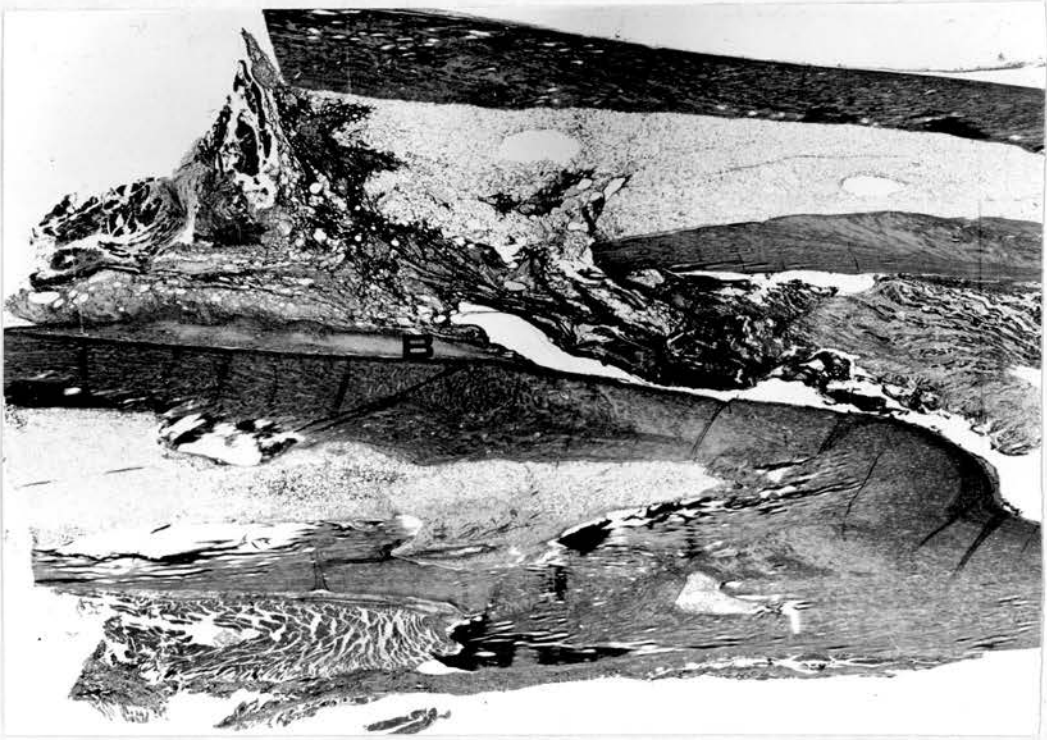


Fig 6.12

The cast-treated fracture at one week. Bony overlap is present and there is a considerable amount of haematoma and inflammatory exudate (A). There is no medullary osteogenesis but periosteal reaction with callus formation is evident (B). (Magnification x6.6).

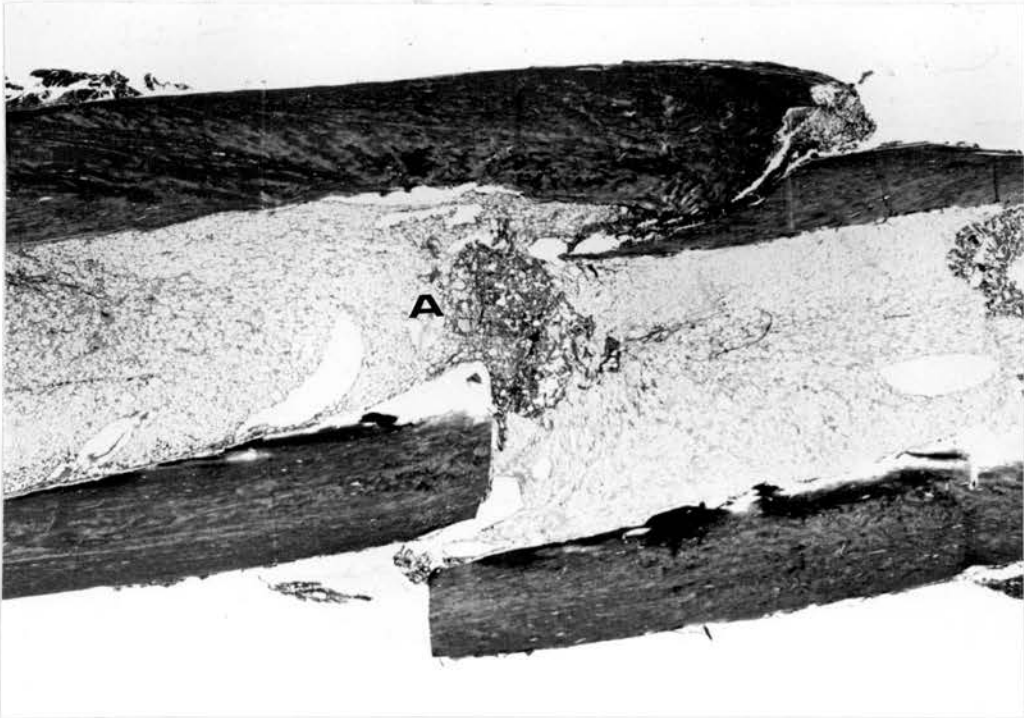


Fig 6.13

The externally fixed fracture at one week. Medullary fibro-vascular tissue is already evident (A) but there is no significant periosteal reaction. There is very little haematoma present. (Magnification x11).

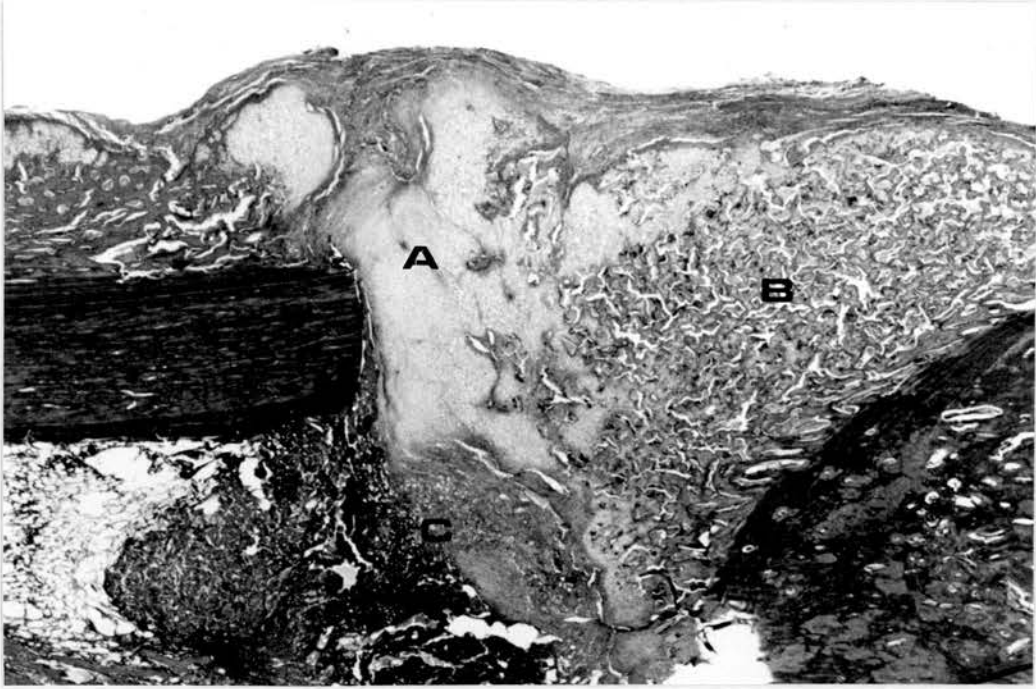


Fig 6.14

The cast-treated fracture at three weeks. There is considerable callus formation and although endochondral ossification of the callus is proceeding quickly (B) large areas of cartilaginous callus persist (A). Haematoma is still present but medullary osteogenesis has started (C). (Magnification x 22.5).

already undergone endochondral ossification. The callus has not, however, bridged the fracture. Review of the three week externally fixed fracture (Fig 6.15) shows that medullary osteogenesis has proceeded quickly and that there is medullary new bone across the fracture. The periosteal reaction is very much less but Fig 6.15A demonstrates that foci of cartilage are present between the bone trabeculae although the little cartilage that has been formed has already undergone endochondral ossification to the extent that there is already periosteal new bone across the fracture site. Callus formation around the fracture site is uneven with more callus being evident on the side of the fracture further away from the fixator.

At six weeks the cast-treated fracture (Fig. 6.16) shows evidence of both intra-medullary and periosteal new bone formation but there is as yet no bone bridging the fracture. Areas of immature hyaline cartilage still exist and the fracture has not yet united. The externally fixed fracture (Fig. 6.17) shows that the medulla is already returning to its pre-fracture state and the cortex adjacent to the fixator is already showing signs of remodelling. The opposite cortex shows periosteal new bone formation. This fracture would appear to be healed and this was confirmed in that after removal of the fixator the bone could not be deformed. The cast-treated fracture was clinically healed by eight weeks at which time the fracture gap had been bridged by bone.

In addition to the constant histological differences in callus formation seen in the externally fixed fractures there is also a striking difference in the cortical bone. By the third week after the fracture (Fig 6.15) a difference in the degree of apparent osteopenia can be seen in the cortical bone adjacent to the fracture site with the cortex further from the fixator being more osteopenic. There is increased osteoclastic activity with bone resorption and the formation of vascular spaces in the cortical bone. At four weeks (Fig. 6.18) the

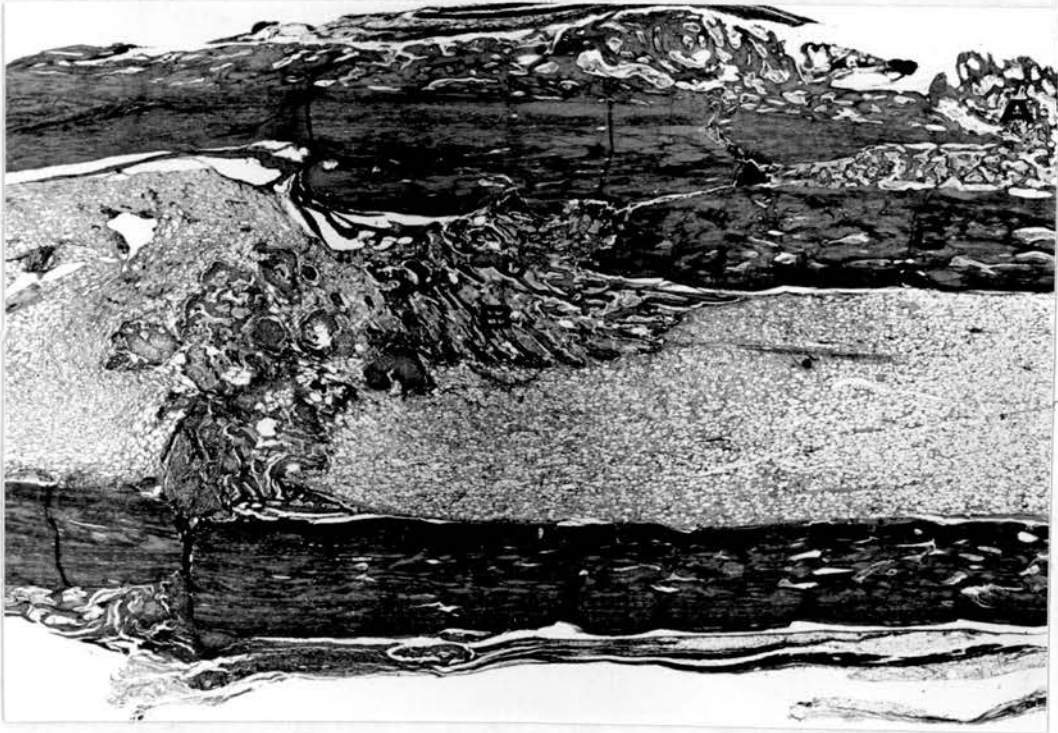


Fig 6.15

The externally fixed fracture at three weeks. The lower cortex was nearer the fixator and the difference in callus formation in the two cortices is clear. Endochondral ossification (A) is proceeding quickly and there are no large areas of cartilaginous callus seen although Fig 6.15A shows that small foci of cartilage exist between the trabeculae confirming the origin of the new bone. Medullary ossification is advanced and the fracture is bridged by both periosteal and medullary new bone. The cortex further from the fixator (C) shows a greater degree of osteopenia than the nearer cortex. (Magnification $\times 10$).

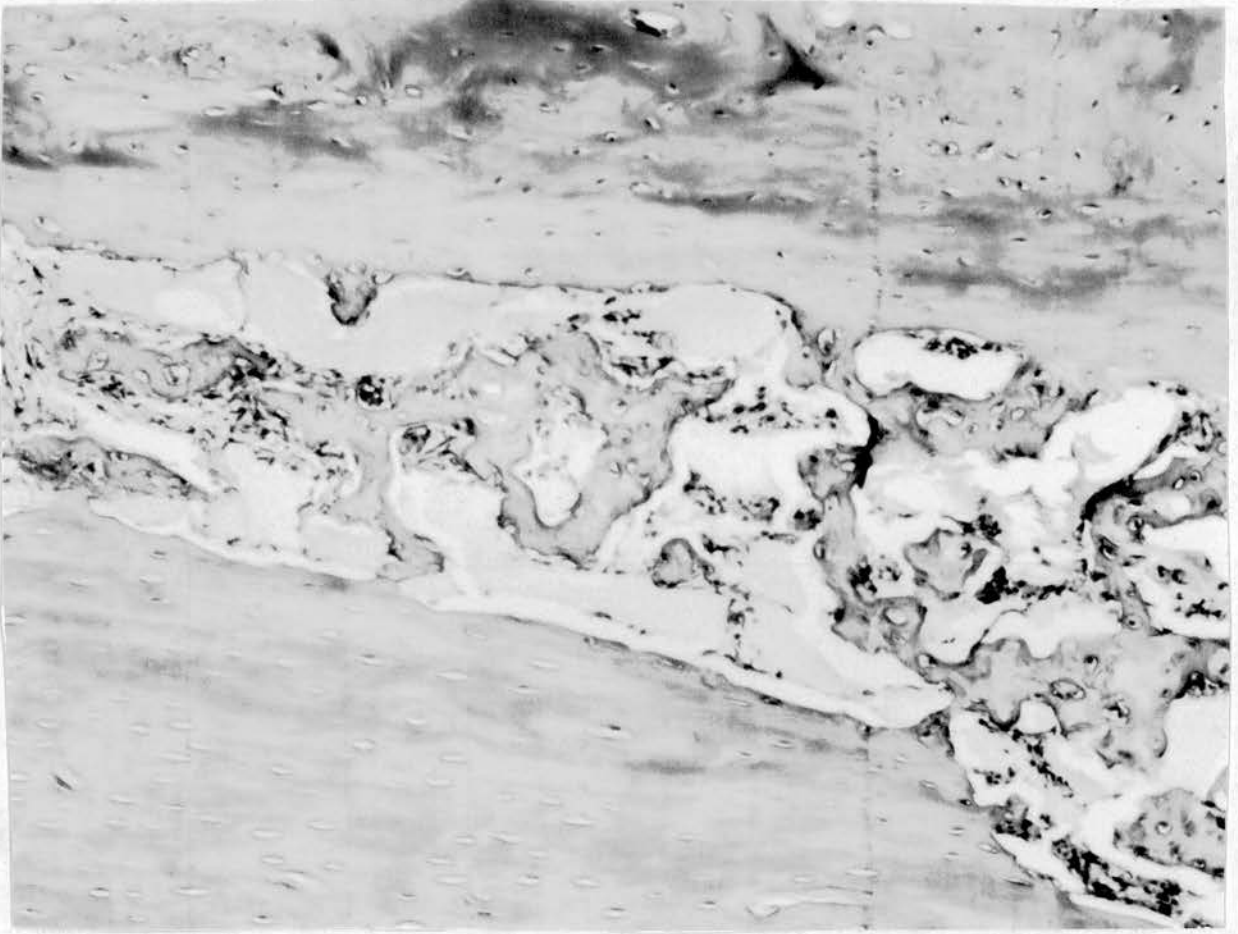


Fig 6.15A

A higher power view of the fracture healing seen in the externally fixed fracture at three weeks. The Goldners Trichrome stain shows up cartilage as a green colour and small foci of cartilage are seen between the new trabeculae. This confirms the cartilaginous origin of at least part of the new bone. (Magnification x45).

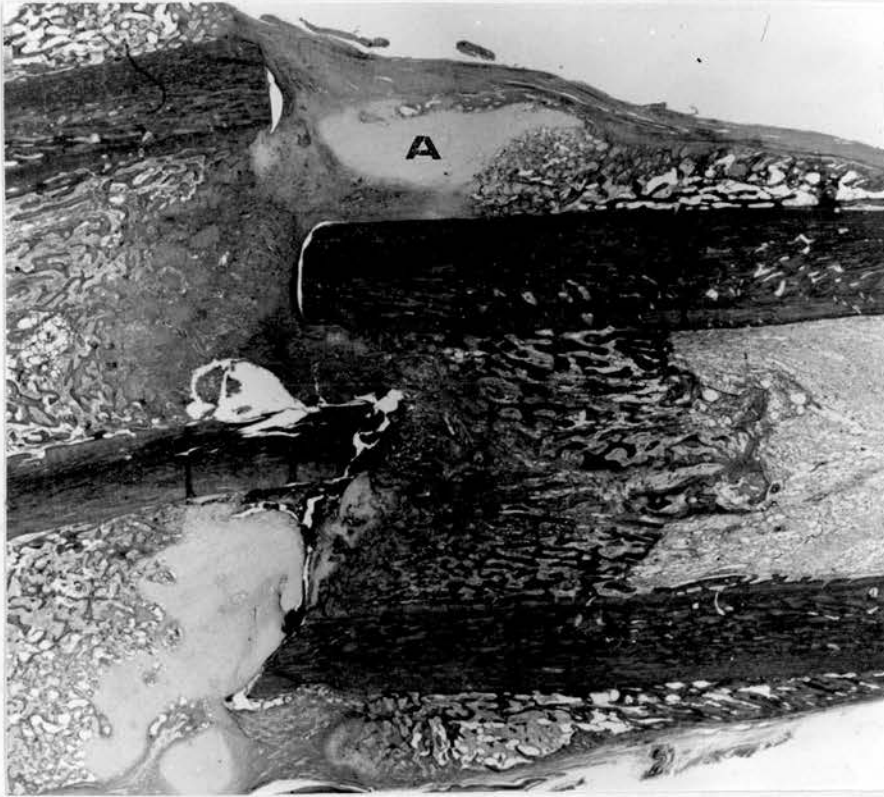


Fig 6.16

The cast-treated fracture at six weeks. Although both endochondral ossification of the periosteal callus and medullary ossification are proceeding the fracture is not yet bridged by bone. Areas of cartilaginous callus persist (A). (Magnification x 9.5).



Fig 6.17

The externally fixed fracture at six weeks. The lower cortex was nearest the fixator and again shows less periosteal reaction than the far cortex. The medulla is returning to its pre-fracture state (A) with the nearer cortex already showing signs of remodelling (B). The further cortex is more osteopenic than the nearer cortex (C). (Magnification x 9.5).

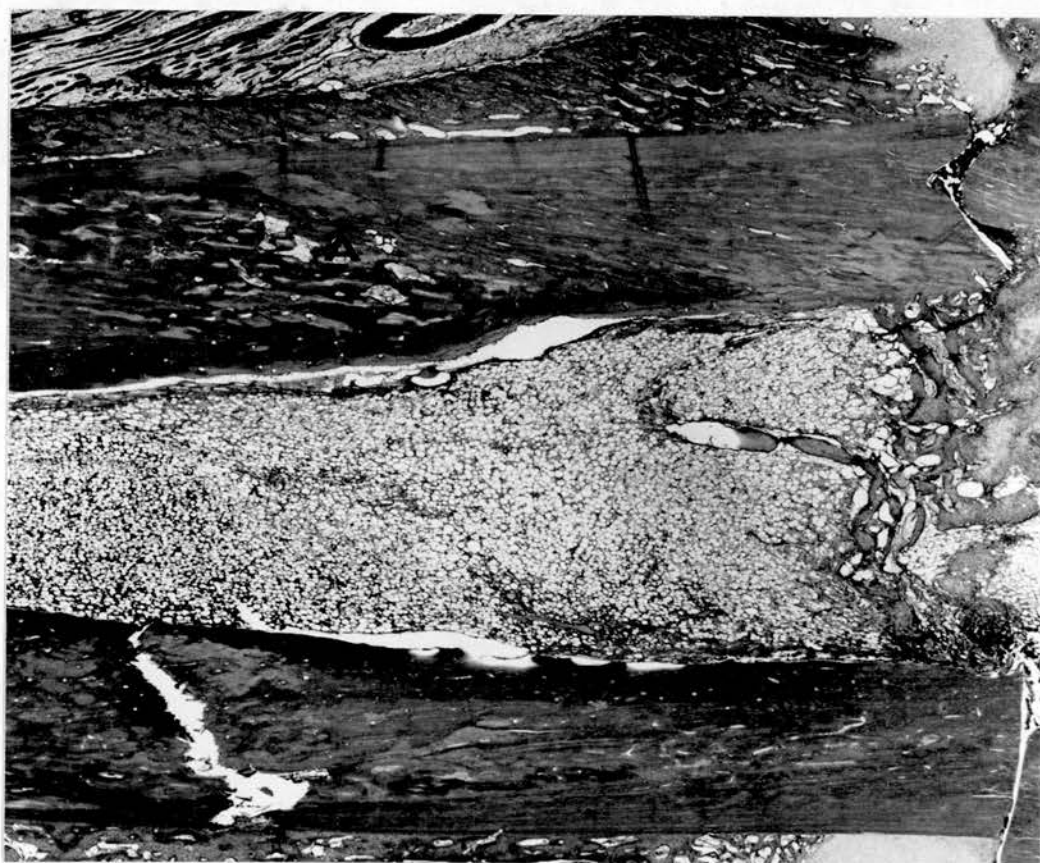


Fig 6.18

The externally fixed fracture at four weeks showing the difference in cortical osteoporosis caused by the enlargement of medullary blood vessels passing through the cortex (A). The lower cortex was nearer the fixator. (Magnification x 15).

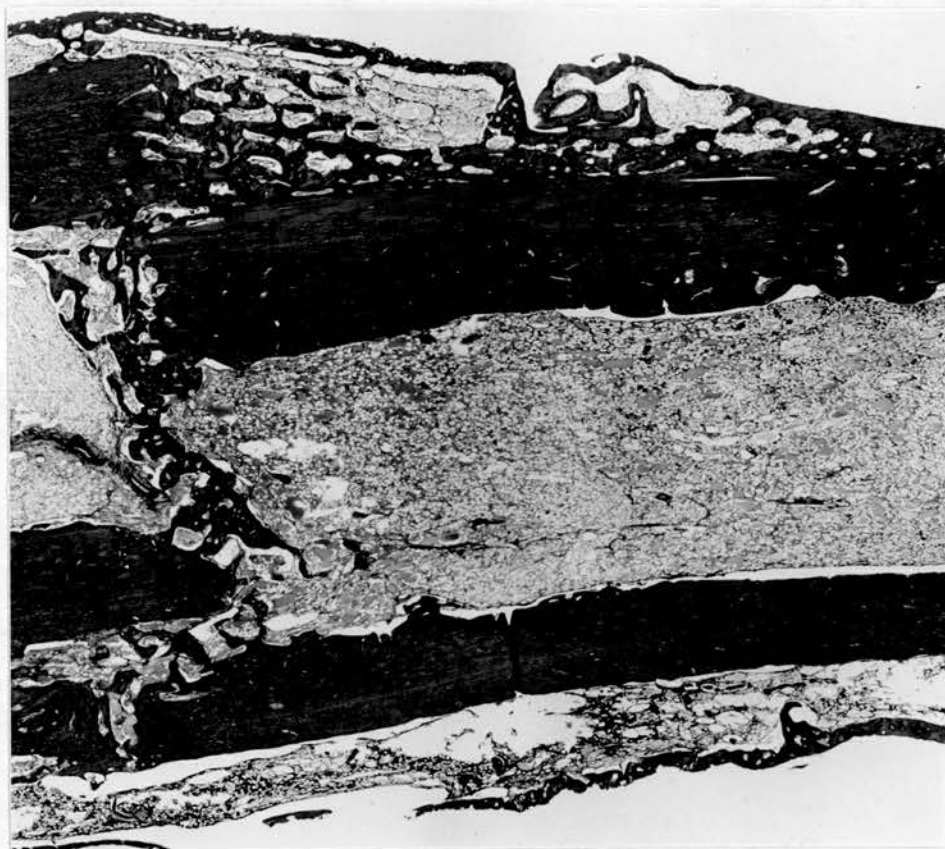


Fig 6.19

The externally fixed fracture at nine weeks showing the appearance of the two cortices to be very similar suggesting that the medullary response is complete. The lower cortex was nearer the fixator. (Magnification x 10.5).

differences in the cortical appearance are more obvious and they have increased further by six weeks (Fig.6.17). By nine weeks (Fig 6.19), after fracture union, the appearance of the cortices is very similar.

Discussion.

Bone blood flow and bone healing in externally fixed fractures has been compared with the same processes in cast-treated fractures which have been extensively studied by other workers. It is accepted that cast treatment of fractures does not provide a constant comparable healing method in terms of stability but the widespread use of casting vindicates its use in this experiment.

Table 6.1 shows that there is a difference in blood flow at the paired fracture sites over most of the ten week period. As only one rabbit was used at each time interval any information to be gained from the results is best obtained by studying the overall trend rather than the individual results. The results show that there are individual differences in microsphere uptake between rabbits and therefore if absolute values for fracture site activity were to be obtained a large number of rabbits would have to be studied at each time interval. The trend indicates little difference in the uptake of microspheres and in the blood flow until the fifth week, following which there is an increasing difference in blood flow up to the tenth week at which point the cast-treated fracture shows a 90.3% increased flow compared with the externally fixed fracture. The explanation of the difference is to be found by studying the histology of the fracture sites.

None of the fractures healed by primary bone union. As compression had not been applied this finding was not unexpected. All the fractures healed by secondary means with callus being present in different quantities at each

fracture site. The externally fixed fractures however showed more medullary osteogenesis than the cast-treated fractures where periosteal healing was more immediate and possibly more important. Medullary ossification in the externally fixed fractures had commenced at week one and was well established by week three. At this time it was only just starting in the cast-treated fractures, the absence of rigidity and the presence of haematoma being detrimental to its establishment. Even after medullary ossification had become established in the cast-treated fractures it was not as important a component in the overall healing process as the endochondral ossification of the periosteal callus. The acceleration of the medullary ossification in the externally fixed fractures was such that the process seemed to have been completed by about six weeks at which time neither medullary or periosteal ossification had stabilised the cast-treated fractures.

In contrast to medullary ossification periosteal reaction was very much more marked in the cast-treated fractures where early callus formation could be seen at one week. By three weeks the cast-treated fractures showed prolific callus but the endochondral ossification of the callus was less advanced than in the externally fixed fractures where the small amount of callus that had formed by this time had been almost completely replaced by new bone.

The vascularisation of the tibial diaphysis of both the rabbit and man, assuming the nutrient artery to be intact, is derived mainly from the medulla aided by small supplements from the periosteal and extra-osseous circulations. Rhinelanders and Wilson (1982) have shown that rigidity of fracture fixation encourages new vessel ingrowth at the fracture site. It would therefore seem that the stability provided by external fixation facilitates ingrowth of new vessels in the medullary circulation thereby encouraging medullary osteogenesis. A further factor contributing to early medullary new bone

formation is the virtual absence of haematoma in the fixed fracture. Rhinelander and Wilson (1982) have also demonstrated that the presence of haematoma and inflammatory exudate slows the ingrowth of new vessels. While haematoma may have a role in providing osteogenic hormones, leucocytes or fibroblasts its physical presence is probably a barrier to new vessel ingrowth just as it is in other tissues. By stabilising the fracture and eliminating the haematoma medullary osteogenesis is accelerated.

A review of the cast-treated fracture sites at weeks one and three (Figs. 6.12 and 6.14) bears out this view of the detrimental role of haematoma and motion at the fracture site. Medullary osteogenesis in the cast-treated fracture can only commence at week three after the haematoma has been resorbed and when the periosteal callus has so stiffened the fracture that conditions suitable for new vessel ingrowth in the medullary circulation exist.

The production of callus has been extensively studied (Urist and McLean, 1941; Yamagishi and Yoshimura, 1955; Brighton and Krebs, 1972; Heppenstall et al, 1975). Several factors have been implicated in the production of callus such as age (Camitz et al, 1934), local oxygen tension (Clark and Clark, 1942; Heppenstall et al, 1975) and endocrine abnormalities (Sissons and Hadfield, 1951; Zadek and Robinson, 1961; Canalis et al, 1977). However Yamagishi and Yoshimura (1955) showed that the differentiation of callus is largely controlled qualitatively, quantitatively and morphologically by local biomechanical factors.

The external fixation provided by the small Hughes device using stiff AO screws as transfixion pins minimises fracture motion to the advantage of medullary osteogenesis but to the detriment of periosteal callus formation. This biomechanical effect is well seen in each externally fixed fracture site as there is more callus visible on the cortex further from the fixator compared

with the stiffer adjacent cortex (Fig 6.20).

The endochondral ossification of callus also differs in the paired fractures. In the cast-treated fractures immature callus persists along with ossified callus up to week ten whereas in the externally fixed fracture at week three almost all the callus has undergone endochondral ossification. It is difficult to know whether increased rigidity increases the rate of endochondral ossification or whether by merely producing less callus to ossify the process is completed in a shorter time. Possibly both factors play a part although it is likely that as new vessel ingrowth is facilitated by stability an acceleration of endochondral ossification occurs.

The relative osteopenic differences seen in the cortices adjacent to the externally fixed fracture sites are also likely to be related to differential stability. Olerud (1968) and Rhineland and Wilson (1982) have both demonstrated cortical erosion by enlarging medullary blood vessels passing through the cortex to vascularise the forming callus, the process commencing at about three weeks after the fracture. It is therefore the increased medullary vascular response which is responsible for this osteopenic condition. The changes are evident between weeks three (Fig 6.14) and four (Fig 6.18) when the medullary response is maximal and although there are obvious changes seen at week six (Fig. 6.17) it is probable that the cortex is starting to revert to its normal state following the slowing of medullary osteogenesis. By week nine (Fig. 6.19) the cortices are almost identical.

This cortical osteopenic condition should not be confused with the stress sparing effect. This process occurs later in plated bones (Uhthoff and Finnegan, 1983) and the osteopenia is seen on the cortex immediately adjacent to the plate. It may occur in externally fixed bone (Terjesen and Benum, 1983) but information on this is scarce.

It is now apparent that the reason for the blood flow

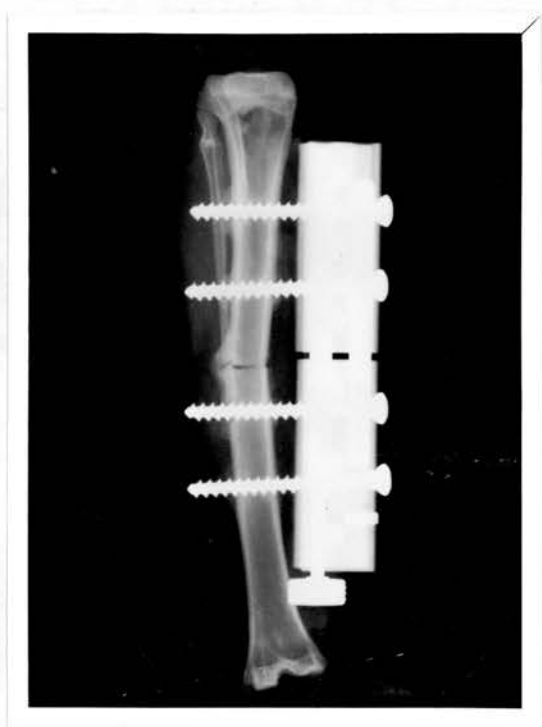


Fig 6.20

The differential callus formation seen in the externally fixed tibiae. More callus was always formed on the cortex further from the fixator the stiffness of fixation decreasing as the distance from the fixator bar increases.

differences shown in Table 6.1 is that callus endochondral ossification and medullary osteogenesis occur at different rates. Endochondral ossification of the relatively avascular cartilaginous callus, with a resulting increase in blood flow, occurs early in the healing process in the cast-treated fracture, but for the first four weeks this is balanced by the increase in medullary blood flow in the externally fixed fracture. After this time however there is a progressive decrease in medullary blood flow in the externally fixed leg accompanied by a continued increase in both endochondral ossification and medullary osteogenesis in the cast-treated leg.

The experiment suggests that if a rigid external fixator is applied to a healing diaphyseal fracture with the nutrient artery intact then:-

- 1) The periosteal reaction is decreased.
- 2) The endochondral ossification of callus is accelerated.
- 3) Medullary osteogenesis is enhanced.
- 4) There is an alteration in the relative importance of periosteal callus formation and medullary ossification in the healing process compared with cast-treated fractures.

A consequence of treating diaphyseal fractures in a cast is that it is usually impossible to retain a fully reduced fracture position. Figure 6.8 illustrates this. However healing in mal-aligned fractures is governed by the same controlling mechanisms that govern perfectly aligned fractures although the requirement for callus formation varies with the degree of mal-alignment. The changes noted between the externally fixed and cast-

treated fractures are therefore due to the rigidity of fixation rather than the alignment of the fractures.

It is difficult to interpret the values for blood flow shown in Table 6.2 beyond saying that they show the flow results for these particular rabbit osteotomies stabilised by fixation methods which impose a particular stiffness. Paradis and Kelly (1975) have published flow rates in dog tibiae after fracture but the tibiae that they studied were rigidly plated and thus were subject to a different biomechanical environment. They showed that flow rates increased after fracture for two weeks and then decreased. These findings have been confirmed by McCarthy et al (1983). It is impossible to compare these results with the results of this experiment as the obvious differences in fracture site activity between different rabbits does not allow accurate comparison. However the figures for the one week fractures compare well with the published figures for intact rabbit tibiae (Lunde and Michelsen, 1970) and dog tibiae (Morris and Kelly, 1980).

SECTION 3

CHAPTER 1

A Review of the Clinical Use of
External Fixation Devices.

The history of external skeletal fixation and its clinical application was discussed in Section 1, chapter 1. The increase in numbers of different fixation devices has been accompanied by an expansion in the indications for their use. In some instances, such as the treatment of the tibial fracture associated with extensive soft tissue loss, the only practical alternative to external fixation is frequently amputation. However it is fair to say that some of the stated indications for external fixation are only indications for fixation whether this be internal or external. This chapter summarises the modern concepts regarding external fixation and highlights the more important indications for its use.

External skeletal fixation in trauma.

A) Long bone fractures.

Table 7.1 details the possible indications for the use of external fixation in the acutely injured patient. Its principal use is in the management of tibial fractures associated with extensive skin or soft tissue loss. Many workers have demonstrated its value in this situation (Fellander, 1963; Vidal et al, 1970; Karlstrom and Olerud, 1975; Jackson et al, 1978; Burney, 1979; Fischer 1982).

Compound tibial fractures have been graded by several workers (Ellis, 1958; Nicoll, 1964; Leach, 1975) with the gradings depending on the amount of bone and soft tissue damage as well as the degree of actual or potential contamination. The classification recommended by Gustilo (1982) has been used in this study as it provides a more thorough assessment of open long bone fractures and it approximates fairly well to other classification systems referred to in the literature (Table 7.2).

Fractures associated with

- soft tissue damage
- soft tissue loss
- neuro-vascular damage
- burns
- bone loss
- comminution
- multiple organ failure

Multiple fractures

Intra-articular fractures

Pelvic fractures

Non-union (infected and uninfected)

Stabilisation of bone following

- arthrodesis

- osteotomy

- massive bone resection

Leg lengthening

Soft tissue stretching

Indications for the use of External Fixation.

Table 7.1

- Type 1. A wound of one centimetre or less and relatively clean. There is a little soft tissue involvement and no crushing component. The fracture is usually a simple transverse or short oblique fracture with minimal comminution.
- Type 2. A laceration more than one centimetre in length without extensive soft tissue damage but with a minimal to moderate crushing component. The fracture is usually a simple transverse or short oblique fracture with minimal comminution.
- Type 3. Extensive soft tissue damage including muscle, skin and neuro-vascular structures. It is often associated with a high velocity injury or a severe crushing component. Includes all open segmental fractures, fractures with with neuro-vascular damage and fractures over eight hours old.

Classification of open fractures.
(Gustilo, 1982).

Table 7.2

There is little debate about the use of external skeletal fixation in the treatment of Type 3 open tibial fractures where there is associated soft tissue damage and impaired bone vascularity (Fig 7.1). The need for stability in this situation is accepted and both unilateral and more complex frames have been successfully used (Edge and Denham, 1981; Edwards, 1979; Behrens, 1982). The combination of external fixation with modern plastic surgery techniques allows good results to be achieved (Fig 7.2).

The treatment of type 1 and 2 open tibial fractures is more controversial as other successful treatment methods such as intra-medullary nailing and plating exist. Frequently the actual choice of treatment method will be dictated by the nature of the particular fracture and the preference of the surgeon. External fixation is useful in Grade 1 and 2 open fractures if there is extensive comminution or if there are other associated fractures or multiple organ failure (Behrens, 1982). Lawyer and Lubbers (1979) and Krempen et al (1979) have used the Hoffmann device to treat closed or grade 1 or 2 open fractures with good results and Burney (1979) used external fixation in a series of 1421 tibial fractures of which about 50% were closed. He has suggested that external fixation is suitable for all tibial fractures but stresses that such external fixation should be of low stiffness.

Kaplan and Pruitt (1980) consider that external fixation is indicated in lower limb fractures associated with extensive burns and Brooker (1979) feels that the only alternative to this - namely traction - is unsatisfactory.

The treatment of established non-union, both infected and uninfected, by external fixation is also well documented (Vidal et al, 1979; Klemm, 1979; Krempen et al, 1979; Ordway, 1982). This is usually combined with bone grafting and may be supplemented with electrical stimulation. Ordway has demonstrated how alteration of

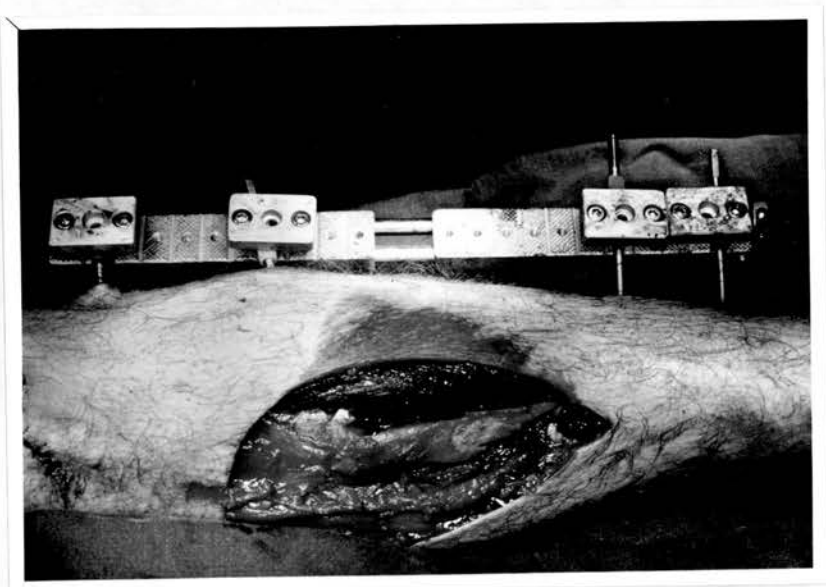


Fig 7.1



Fig 7.2

The same grade 3 compound tibial fracture after the original wound excision and application of the Hughes fixator (7.1) and one year later (7.2) after a myocutaneous flap based on the medial half of gastrocnemius had been used to gain skin closure. Union was complete.

the biomechanical environment alone by the application of an external fixation device can cause a hypertrophic non-union to unite without bone grafting. The external fixation of infected non-union allows for adequate bone resection and provides the necessary conditions for successful bone grafting (Burri, 1983). The technique of Papineau bone grafting (Papineau, 1973) is particularly facilitated by rigid external fixation (Burney and Rasquin, 1983) and a healing rate of 95% in infected non-unions has been reported (Roy-Camille et al, 1976).

Bone grafting may also be necessary if bone loss is present and the preservation of bone length can best be accomplished using external fixation. Olerud (1979) has shown the usefulness of external fixation in stabilising a tibia while vascularised free fibular grafts are used to restore tibial length.

Certain external fixation devices permit closed distraction of tibial fractures. This may be necessary after a period of inadequate initial fracture treatment or after a delay caused by the treatment of a co-existing problem such as a head injury. If the overlap is considerable then slow progressive distraction may be required to regain the appropriate length. This was carried out successfully in two patients in this series.

One use for external skeletal fixation which has not received attention in the literature is the stabilisation of tibial fractures following fasciotomy. A fasciotomy is usually performed following the establishment of a compartment syndrome in a closed or minimally compound fracture. Following fasciotomy fractures are difficult to treat conservatively and the Hughes device has been used to stabilise eight tibial fractures where a fasciotomy has been required (Fig 7.3).

The tibia is not the only long bone in which fractures have been stabilised with external fixation. However as grade 3 fractures are more common in the tibia than in the femur or the long bones of the upper limb its use with other bones is limited, the main indication being a

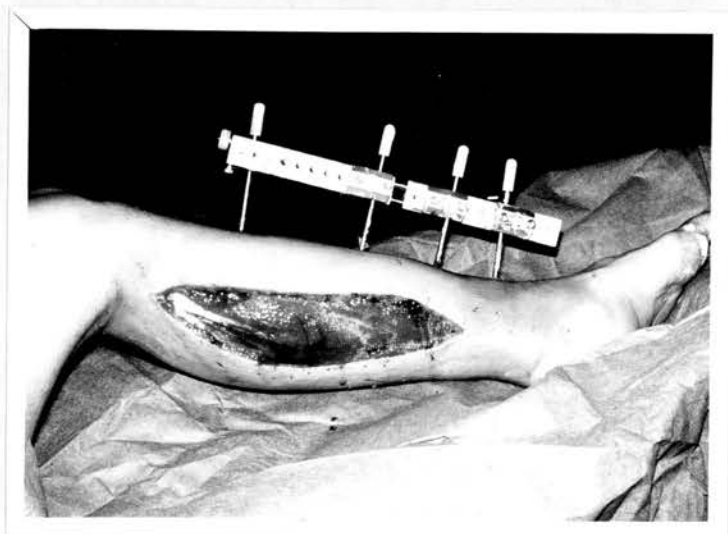


Fig 7.3

The Hughes external fixator has been found to be useful in stabilising tibial fractures in limbs where a fasciotomy has been required.

grade 3 compound fracture. Other treatments are frequently employed for less severe fractures. The absence of a subcutaneous border in long bones other than the tibia means that muscle penetration is inevitable and this can lead to pin track sepsis and stiffness in adjacent joints.

Despite these potential problems external fixation has been advocated in the treatment of femoral fractures (Ronen et al, 1974; Seligson and Kristiansen, 1978). Hughes and Sauer (1982) have described the use of the Wagner device in the treatment of comminuted subtrochanteric fractures and Edwards (1979) has shown that the Hoffmann device can be used to stabilise a distal femoral fracture.

The use of external fixation in the treatment of uncomplicated long bone fractures in the upper limb is rare. Kamhin et al (1977) reported on the external fixation of six humeral fractures four of which were closed injuries. The other two were treated following failed internal fixation. Their results were satisfactory but they still concluded that external humeral fixation was mainly indicated for the treatment of Grade 3 open fractures.

Henderson et al (1983) described the successful use of external fixation in diaphyseal fractures of the radius and ulna but concluded that its use should be restricted to severe fractures and they advocated the use of plating or intra-medullary fixation for less complicated fractures.

The tubular bones of the hand have also been externally fixed (Dickson, 1975; Klemm, 1979; Oganessian, 1983). Klemm recommends its use in the primary fusion of comminuted digital intra-articular fractures and to facilitate digital reimplantation. Dickson has shown how a comparatively simple external fixator can be used to treat metacarpal fractures.

B) Intra-articular fractures

External fixation has been found to be of greater value in the upper limb in the treatment of comminuted intra-articular fractures. These can often only be adequately reduced by applying a distraction force across the joint and relying on the intact adjacent soft tissue to mould the fracture fragments into a satisfactory position. This concept has been labelled "ligamentotaxis" by Vidal et al (1979) who have reported on the use of distraction fixation in the hip, knee, ankle and wrist. The treatment of distal radial fractures with intra-articular comminution (Fig 7.4) has received much attention in the literature (Cole et al, 1966; Cooney et al, 1979; Vidal et al, 1979; Forgon and Mammel, 1981). It is suggested that distraction fixation gives good results in treating these fractures in the younger patient (Fig 7.5).

Letournel (1982) has advocated the use of the Judet fixator for the treatment of ankle fractures associated with skin loss, infection or a crush injury to the lower limb. His indications are similar to those for diaphyseal fractures and are infrequently seen.

Oganesyan (1982) has described the use of his circular or semi-circular frames to facilitate joint movement. The principle is that the fixator is hinged opposite the joint to be mobilised and the bones are securely fixed proximally and distally with transfixion pins. Active joint movement is then encouraged. He advocates its use in the treatment of joint contractures, in the reduction of dislocations and in the fixation of peri-articular fractures. It is claimed that this treatment restores articular congruity by facilitating not only the production of fibro-cartilage but also that of hyaline cartilage.



Fig 7.4



Fig 7.5

A comminuted distal radial fracture in a 34 year old male prior to treatment (7.4) and after a Hoffmann external fixator had been applied with distraction (7.5). The fixator was retained for eight weeks and the eventual function was good.

C) Pelvic fractures.

External skeletal fixation can be used to treat pelvic fractures for two reasons. Severe pelvic fractures are often associated with massive haemorrhage, sciatic nerve injuries and bladder and visceral disruption. Rigid stabilisation can minimise blood loss and facilitate soft tissue healing in the pelvis just as it does in grade 3 tibial fractures. Haemorrhage following pelvic fracture can be severe and although internal fixation can be successful (Whiston, 1953; Jenkins and Young, 1978) it can be hazardous in the acute situation. Trunkey et al (1974) have outlined the considerable problems of treating such fractures conservatively. External fixation offers particular advantages in this situation.

In addition to stabilising soft tissue injuries it has been suggested that external pelvic fixation can be used to treat certain fractures and dislocations (Slatis and Karaharju, 1980; Sahlstrand, 1979; Grosse, 1979; Mears and Fu, 1980; Tile, 1984). Grosse has suggested that external pelvic fixation can be used to treat pubic symphysis and sacro-iliac dislocations as well as transverse acetabular fractures and central fracture dislocations. Mears (1979) also suggests its use in central fracture dislocations as well as in the treatment of unstable pelvic ring fractures. Johnston (1979) has advocated its use in the treatment of Malgaigne or vertical shear fractures. Tile (1984) has reviewed over 250 pelvic fractures and has also examined the biomechanics of external pelvic fixation. He has concluded that if the posterior sacro-iliac ligaments are disrupted in addition to the anterior ligaments then external fixation does not provide sufficient stabilisation to permit acceptable maintenance of joint reduction. Under these circumstances he advocates internal fixation of the sacro-iliac joint. He does not advocate the use of external fixation in the treatment of acetabular fractures.

The results of treating pelvic fractures with external fixation are difficult to assess as the relatively low numbers of patients makes analysis difficult. However there is little dispute as to their use in the initial management of the unstable pelvis particularly if there is severe haemorrhage. Tile's work suggests that they are less useful in treating fractures or dislocations than was first thought.

External skeletal fixation in elective surgery.

The most frequent uses of external skeletal fixation in elective or non-traumatic orthopaedic surgery are in leg lengthening (Wagner, 1976) and arthrodesis (Charnley, 1953). Although all external fixators that permit distraction and compression can be used the Wagner device is used most commonly for leg lengthening and probably the Charnley clamp for arthrodesis although Mears (1979) has illustrated the use of the Hoffmann fixator in arthrodesis of all the major joints. Schroder and Frandsen (1983) have recently outlined the advantages of external fixation in shoulder arthrodesis.

Any long bone osteotomy can be stabilised by external fixation but most surgeons would advocate the use of internal fixation if the soft tissue damage is minimal and the risk of infection low.

Olerud (1979) has used the Hoffmann to stabilise a pelvic osteotomy carried out for bladder extrophy. He has also used the device for the stabilisation of a long bone after tumour resection and for the progressive correction of knee contractures in a patient with congenital webbing.

SECTION 3

CHAPTER 2

A Study of the Clinical Use of the
Hughes External Fixator.

The Hughes external fixation device has been in extensive clinical use since March 1980 and the results of a prospective study of its use between March 1980 and March 1983 are presented. During this period the device was used 62 times although 3 patients died prior to the fixator being removed and their results have not been included in the series. A total of 52 acute fractures, 3 non-unions, 3 osteotomies and 1 arthrodesis were treated.

Prior to March 1980 rather limited use had been made of the device and a retrospective study of the results of treatment of 5 non-unions, 2 acute fractures and 2 osteotomies is presented. No acute tibial fractures treated before March 1980 are presented as their data is incomplete.

The relative numbers and usage of the Hughes device in this series is presented in Table 8.1.

Tibial diaphyseal fractures.

A total of 48 tibial fractures were treated with the Hughes external fixation device between March 1980 and March 1983. One woman sustained bilateral fractures and therefore 34 males and 13 females were treated. The age range was 13-80 years with a mean age of 36.9 years. The age distribution in decades is shown in Figure 8.1.

Table 8.2 shows the distribution of the tibial fractures. These were mostly in the middle and lower thirds with few upper third fractures being treated

Of the 48 tibial diaphyseal fractures there were 9 closed, 2 Grade 1, 25 Grade 2 and 12 Grade 3 open fractures. External fixation was used in the Grade 3 fractures because of the associated soft tissue injuries. Sixteen of the Grade 2 fractures were treated by primary external fixation and 9 were treated secondarily because of failure of conservative management. Both the Grade 1 fractures were short oblique fractures primarily treated with external fixation. Five of the closed fractures were

<u>Acute fractures</u>	<u>Number</u>
Tibial stabilisation	48
Tibial distraction	1
Humeral stabilisation	3
Pelvic stabilisation	<u>3</u>
Total	55
 <u>Non-unions</u>	
Tibial	5
Femoral	<u>3</u>
Total	8
 <u>Osteotomies</u>	
Tibial	5
 <u>Arthrodesis</u>	
Knee	<u>1</u>
 <u>Overall total</u>	69

The distribution and relative numbers of the conditions treated with a Hughes external fixator.

Table 8.1

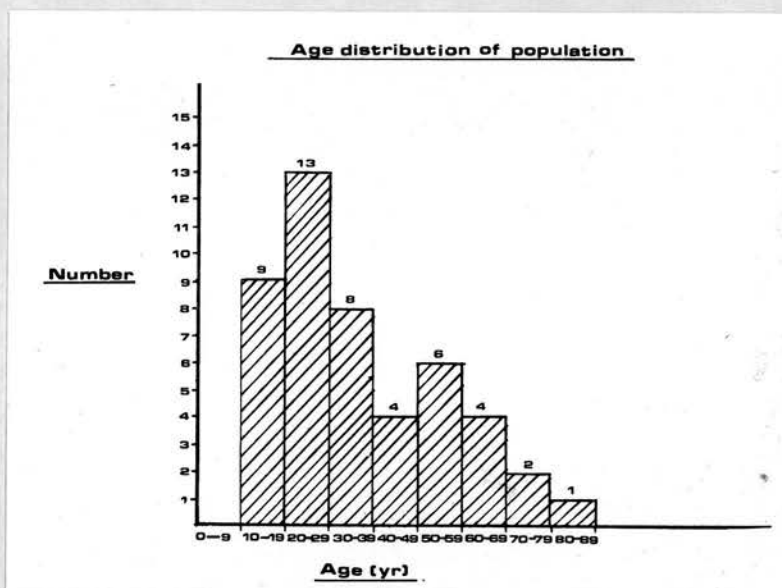


Fig 8.1

The age distribution of the patients with tibial diaphyseal fractures treated with the Hughes fixator.

Location of fracture	Number	Percentage
Upper third	3	6.2
Middle third	18	37.5
Lower third	19	39.5
Segmental	8	16.5

Relative numbers and percentages of the fractures in different areas in the tibia.

Table 8.2

externally fixed because fasciotomies were performed and 2 because of failure of conservative management. One closed segmental fracture and 1 tibial fracture in a tetraplegic were also externally fixed. All external fixators were applied under antibiotic cover.

Fracture healing was obtained in all cases except in 1 closed and 1 grade 2 open fracture which remain unhealed after eight months and one year respectively. Two of the grade 3 fractures required eventual amputation and the time to union for the remaining 44 fractures is presented in Table 8.3.

Ellis (1958) showed that minor degrees of compounding did not significantly prolong healing time and therefore the results of the low number of Grade 1 open fractures have been added to the results of the closed fractures. Collectively they provide a comparison for the results of the grade 2 and 3 open fractures. Table 8.3 shows that the severity of the fracture affects the overall healing time. In addition to this the effect of other parameters on the overall healing time was also studied. Differences in pin angle, pin location and pin length were examined taking into account the biomechanical results presented in Section 1, chapter 4. The effect on the healing time of altering the fixator position was examined as was the initial reduction and duration of fixator application.

A) Pin angle.

Many of the fixators were applied using four parallel pins set at 90 degrees to the bone. However individual clinical circumstances frequently dictated that other pin angles were used and the effect of this was examined. In view of the biomechanical finding that convergence of the inner pins up to 15 degrees did not greatly affect the overall stiffness but that a similar divergence of the outer pin did, the patients have been divided into two groups depending on the pin angle and the resultant stiffness. In group 1 all the pins were at 90 degrees to

Fracture grade	Number	Average union time (wk)
Closed	8	27.7
1	2	35.0
Closed+1	10	29.2
2	24	26.7
3	10	44.5

Average time to union for the different grades of tibial fracture. As in all the figures the results for the closed and grade 1 have been combined for comparative purposes because of the small sample size of the grade 1 fractures.

Table 8.3

the bone or the inner pins converged at an angle up to 15 degrees. Group 2 contains the other configurations. Based on the biomechanical results group 1 has a higher overall stiffness than group 2. The results are shown in Table 8.4 and it is clear that not only is there no significant difference between the two groups ($p > 0.5$) but that there is little difference when compared with the overall healing times for the different fracture grades shown in Table 8.3. Statistical analysis of all the data in this survey was performed using a permutation t test.

Despite the small sample sizes the results in Table 8.4 suggest that the stiffness provided by all the different pin angle configurations is adequate to stabilise the fracture and that any stiffness difference caused by pin angulation is not sufficient to alter the healing time greatly.

B) Pin location.

To investigate the effect of pin location on time to union it was again necessary to divide the fractures into two groups based on the biomechanical results. These showed that the stiffness varied directly with the distance between the two outer pins and indirectly with the distance between the two inner pins in a four pin system and that the addition of more pins did not alter the stiffness. In this case Group 1, the more stable group, consists of the fractures stabilised with a configuration where the outer pins are at least 20cm apart and the inner pins are less than 8cm apart. Group 2 contains the other, less stable, configurations. The results are shown in Table 8.5 which indicates that there is no significant difference between the union times in the two groups ($p > 0.5$). Comparison with Table 8.2 shows that there is little difference when compared with the overall time to union for the different grades. Despite

Group 1			Group 2	
Fracture grade	No.	Average union time (wk)	No.	Average union time (wk)
Closed	6	30.0	2	21.0
1	1	52.0	1	18.0
Closed+1	7	33.1	3	20.0
2	17	26.2	7	28.0
3	6	42.4	4	49.2

The effect of pin angulation on time to union in the different grades. The fractures have been divided into two groups depending on the stiffness of fracture fixation.

Statistical analysis shows no significant difference between the two groups ($p > 0.5$).

Table 8.4

Fracture grade	Group 1		Group 2	
	No.	Average union time (wk)	No.	Average union time (wk)
Closed	4	22.5	4	32.2
1	1	52.0	1	18.0
Closed+1	5	28.2	5	28.6
2	9	24.5	15	28.6
3	2	50.0	8	43.9

The effect of pin location on the time to union in the different fracture grades. The fractures have been divided into two groups depending on the stiffness of fracture fixation.

Statistical analysis shows no significant difference between the two groups ($p > 0.5$).

Table 8.5

the small sample size this suggests that there is no significant difference in the time to union for the different pin locations.

C) Effective pin length.

The effect of varying the distance between the limb and the fixator bar was examined. For the purposes of comparison the fractures were divided into three groups depending on this distance. As all the fixators were placed between 2.0 and 6.5cm from the limb the three groups were defined as Group 1 (2.0 - 3.5cm), Group 2 (3.6 - 5.0cm) and Group 3 (5.1 - 6.5cm). Where a fixator was applied at an angle to the limb the mid-point was measured and used. Table 8.6 shows the results.

Statistical analysis shows no significant difference in the three groups of results ($0.4 > p > 0.2$). Altering the effective pin length does not seem to have any definite effect on union time.

D) Fixator location.

As previously mentioned the tibia can be externally fixed using either a laterally or an antero-medially placed unilateral device. In the 44 patients that went on to successful union in this series 12 had a laterally placed device and 32 were placed on the antero-medial subcutaneous tibial border. The choice of location was often dictated by the site and extent of the soft tissue damage. The effect on healing times is shown in Table 8.7. This suggests a shorter healing time for the antero-medially applied device in the Grade 2 and 3 open fractures but again the statistical differences are not significant ($0.5 > p > 0.4$) and firm conclusions are

Fracture grade	Effective pin length					
	2.0 - 3.5cm		3.6 - 5.0cm		5.1 - 6.5cm	
	No.	Av. union time (wk)	No.	Av. union time (wk)	No.	Av. union time (wk)
Closed	2	13.5	4	23.5	2	50.0
1	2	35.5	0	0	0	0
Closed+1	4	24.2	4	23.5	2	50.0
2	9	31.2	5	19.6	10	26.3
3	3	34.6	5	47.2	2	52.5

The effect of altering the effective pin length on time to union in the different grades.

Statistical analysis shows no significant difference between the three groups ($0.4 > p > 0.2$).

Table 8.6

Fracture grade	Location on tibia			
	Antero-medial		Lateral	
	No.	Average union time (wk)	No.	Average union time (wk)
Closed	8	27.2	0	0
1	1	52.0	1	18.0
Closed+1	9	30.0	1	18.0
2	20	23.9	4	41.0
3	3	31.3	7	44.8

The effect of altering the location of the fixator bar on time to union in the different grades

Statistical analysis shows no significant difference between the two groups ($0.5 > p > 0.4$).

Table 8.7

impossible. It is in fact quite possible that the use of the lateral location reflects a medial or antero-medial skin defect which may well prolong the healing time in the subjacent tibia.

E) Initial reduction and duration of fixation.

To investigate the effect on healing time of a good initial reduction and a prolonged external fixation time only the Grade 2 fractures have been examined. The relatively low numbers of closed and grade 1 fractures makes their analysis difficult and many of the grade 3 fractures are comminuted and impossible to adequately reduce. In addition grade 3 fractures are often externally fixed for a long period because of the severity of the soft tissue damage.

Of the 24 grade 2 open fractures that proceeded to union 14 had a virtually anatomical reduction and 10 were reduced with a deformity of at least 5 degrees in at least one plane. These were defined as mal-reduced. There was a clinical impression that removal of the fixator at four weeks was accompanied by poor results and a period of six weeks was used for comparison. The Grade 2 fractures were therefore divided into four groups based on their initial reduction and the duration of fixation. The results are shown in Table 8.8. Where a good initial reduction has been carried out and the fixator has been applied for 6 weeks or more then the time to union is considerably less than in the other three groups where either one or both of these criteria have not been fulfilled. It is of interest that bone grafting was never required to achieve union in this group whereas a relatively high rate of bone grafting is seen in the other groups. Statistical analysis shows no significant difference in the union times in the first group compared with the other three ($0.47 > p > 0.2$).

	Number	Average union time (wk)	Number bone grafted
Good reduction Fixator \gg 6wk	10	18.3	0
Good reduction Fixator \ll 6wk	4	30.7	2
Mal-reduction Fixator \gg 6wk	4	41.3	3
Mal-reduction Fixator \ll 6wk	6	29.3	2

The effect of initial reduction and duration of fixation on the time to union in grade 2 open tibial fractures. The number of bone grafts in each group is also shown.

The difference between the union time for the first group and the times for the other three groups does not reach statistical significance ($0.4 > p > 0.2$).

Table 8.8

Non-union.

The definition of non-union is difficult. Frequently an arbitrary time is used and if a fracture is not healed at this time it is said to be a non-union. The subsequent treatment is usually bone grafting.

As fracture healing varies with several factors such as the type of fracture, the affected bone and the degree of soft tissue involvement the application of a particular time limit is often not helpful. Grade 3 open tibial fractures would be expected to take longer to heal than grade 1 fractures. It is also unreasonable to define non-union purely in terms of the need for bone grafting as fractures bone grafted early might have healed later without grafting. In view of these difficulties the non-union rate is not presented.

In this series 1 patient had an amputation 2.5 weeks after injury. Of the remaining 47 patients 22 (46.8%) were bone grafted in the belief that they would proceed to non-union. Nineteen of the bone grafts were performed at 18 weeks or later and therefore might be considered proven non-unions. The remaining three were bone grafted at 13, 14 and 15 weeks and as they were all in closed fractures it is theoretically possible that union might have occurred without grafting. The actual breakdown of bone graft rates according to fracture grade is shown in Table 8.9.

As expected the Grade 3 open fractures had a high rate of bone grafting. One patient with a segmental fracture required a second bone graft which was not included in Table 8.9. The bone grafting rate in the closed and grade 1 group was surprisingly high being almost twice that of

Fracture grade	Number	Percentage	Range (wk)	Average time (wk)
Closed	5	55.5	13 - 33	19.4
1	1	50.0	34	34.0
Closed+1	6	54.5	13 - 34	21.8
2	7	28.0	13 - 63	35.6
3	9	81.8	18 - 63	25.0

The relative numbers, percentages, time ranges and average time to bone grafting in the different fracture grades.

Table 8.9

the grade 2 group. It is also interesting that the closed and grade 1 group along with the grade 3 group were bone grafted at an earlier stage than the grade 2 group. The possible reasons for this will be discussed later.

Mal-union.

In addition to facilitating bone healing the avoidance of mal-union is also a prerequisite of a good fracture stabilisation method. In this series a satisfactory result is defined as one where there is less than 5 degrees of angular or rotational deformity and less than one centimetre of bone shortening (Edge and Denham, 1981). Using these criteria and excluding the 2 fractures not yet healed and the 2 amputations 17 of the 44 fractures (38.6%) healed in a malunited position. A breakdown of these mal-unions according to fracture grading is shown in Table 8.10.

There is a remarkable similarity in the mal-union rates throughout the fracture grades suggesting that residual deformity does not depend on grade but on other factors. The position of the fracture in the tibia seems to be important. Table 8.11 details the mal-union rates according to fracture position.

The mal-unions were further examined to see if changes in pin angle, pin location, effective pin length, fixator location, initial reduction or duration of fixation were implicated in their production.

A) Pin angle.

The fractures were divided into two groups depending on their pin angle configuration in the same way as in the

Fracture grade	Satisfactory result	Mal-union numbers	Percentage mal-unions
Closed	5	3	26.6
1	1	1	50.0
Closed+1	6	4	40.0
2	15	9	36.0
3	6	4	40.0

The relative numbers of satisfactory results and mal-unions and the percentage of mal-unions in the different fracture grades.

Table 8.10

Fracture location	Number of mal-unions	Percentage mal-unions
Upper third	1	33.3
Middle third	6	33.3
Lower third	9	47.4
Segmental	1	12.5

Numbers and percentages of mal-unions in the different fracture locations.

Table 8.11

study on bone union (Table 8.4). A total of 70.6% of the mal-unions and 66.6% of the satisfactory unions followed a group 1 or stiffer pin angle configuration. The breakdown for the different fracture grades is shown in Table 8.12. No obvious trend can be seen and statistical comparison between groups 1 and 2 in the satisfactory result and mal-union groups shows no significant difference ($0.4 > p > 0.2$). Most unions, whether satisfactory or not, follow a group 1 pin angle configuration. This suggests again that all the pin angle configurations provide sufficient stability to hold a fracture satisfactorily.

B) Pin and fixator location.

Using the same definitions for groups 1 and 2 as used for the study of the healing times (Table 8.5) the effect of pin location on the rate of mal-union was investigated. Table 8.13 details the results. A similar percentage of satisfactory and mal-unions occur in both groups with no significant difference being found ($0.4 > p > 0.2$). Moving the fixator to the anteromedial border also had no effect on the mal-union rate.

C) Effective pin length.

Using the different ranges of pin length already detailed in the section on bone union a comparison of the numbers of mal-unions in the three ranges shows that 4 mal-unions occurred with the bar 2.0 - 3.5cm from the limb, 5 at 3.1 - 5.0cm and 8 at 5.1 - 6.5cm. A detailed breakdown according to fracture grading is shown in Table 8.14 which shows a trend towards more satisfactory union where the effective pin length is between 2.0 - 3.5cm. However the sample size is small and there is no statistically significant difference even between the satisfactory

	Satisfactory result		Mal-union	
Fracture grade	Group 1	Group 2	Group 1	Group 2
Closed	4	1	2	1
1	0	1	1	0
Closed+1	4	2	3	1
2	10	5	7	2
3	4	2	2	2

The effect of pin angulation on the number of satisfactory results and mal-unions. The patients have been divided into two groups depending on the stiffness of fracture fixation.

Statistical analysis shows no significant difference between groups 1 and 2 in either the satisfactory result or mal-union patients ($0.4 > p > 0.2$). There is also no significant difference between the two group 1 ($0.5 > p$) or the two group 2 ($0.4 > p > 0.2$) pin locations.

Table 8.12

	Satisfactory result		Mal-union	
Fracture grade	Group 1	Group 2	Group 1	Group 2
Closed	3	2	1	2
1	0	1	1	0
Closed+1	3	3	2	2
2	5	10	3	6
3	1	5	0	4

The effect of pin location on the number of satisfactory results and mal-unions. The patients have been divided into two groups depending on the stiffness of fracture fixation.

Statistical analysis shows no significant difference between groups 1 and 2 in either the satisfactory result or mal-union patients ($0.4 > p > 0.2$). There is also no significant difference between the two group 1 ($0.5 > p$) or the two group 2 ($0.5 > p > 0.4$) pin locations.

Table 8.13

	Effective pin length					
	2.0 - 3.5cm		3.6 - 5.0cm		5.1 - 6.5cm	
Fracture grade	Satis. result	Mal-union	Satis. result	Mal-union	Satis. result	Mal-union
Closed	2	0	3	1	0	1
1	1	1	0	0	0	0
Closed+1	3	1	3	1	0	1
2	6	3	4	1	0	1
3	3	0	2	3	1	1

The effect of changing the effective pin length on the numbers of satisfactory results and mal-unions.

Statistical analysis shows no significant difference in the numbers of satisfactory results and mal-unions within each of the three groups ($0.4 > p > 0.2$). There is also no significant difference in the satisfactory results for the 2.0 - 3.5cm and the 5.1 - 6.5cm groups ($0.2 > p > 0.1$).

Table 8.14

results in the 2.0 - 3.5cm and the 5.1 - 6.5cm groups ($0.2 > p > 0.1$).

D) Initial reduction and fixator duration.

As with the bone healing studies the importance of initial reduction and duration of fixation in the production of mal-union has been studied. Table 8.15 lists the results. These show that 28 (96.5%) of the good results occurred after good initial reduction and 19 (65.5%) occurred after good reduction and at least six weeks of external fixation. Only one bad result followed an initially good reduction and six weeks of external fixation. This occurred in a grade 1 open fracture which lost position after an initially satisfactory reduction. Again the low sample size means that there is no statistically significant difference in the number of satisfactory results and mal-unions following good initial reduction ($0.4 > p > 0.2$).

Examination of the 17 mal-unions shows that 11 (64.7%) followed a bad initial reduction and only 1 (5.9%) followed a good reduction and at least six weeks fixation. These results suggest that, as for bone union, there is a positive relationship between the initial reduction, the duration of fixation and the mal-union rate.

Breakdown of the mal-unions shows that the commonest deformity is recurvatum which occurred in 11 (64.7%) of the cases. The range of recurvatum was 8 - 30 degrees with a mean of 16.5 degrees. In 2 cases the recurvatum was associated with a varus deformity and in 1 with significant shortening. There were 3 varus mal-unions of between 12 and 34 degrees (mean - 20 degrees) and 1 valgus deformity of 12 degrees. There were 6 cases of shortening of between 2.5 and 5.0cm (mean - 2.9cm).

	Satisfactory result		Mal-union	
	Number	Percentage	Number	Percentage
Good reduction Fixator ➤ 6wk	19	65.5	1	5.9
Good reduction Fixator < 6wk	9	31.0	5	29.4
Mal-reduction Fixator ➤ 6wk	0	0	5	29.4
Mal-reduction Fixator < 6wk	1	3.5	6	35.3

The effect of the initial reduction and the duration of fixation on the relative numbers and percentages of satisfactory results and mal-unions.

Statistical analysis shows no difference in the number of satisfactory results and mal-unions following a good initial reduction ($0.4 > p > 0.2$).

Table 8.15

Callus formation.

The rabbit experiments indicated that little callus was formed during bone healing although primary bone union did not occur. They also showed that more callus was formed on the side of the fracture further from the fixator (Fig 6.20). These findings were confirmed in the clinical series with little callus being formed in any of the fractures. The distribution of the callus varied but 12 of the 25 fractures that healed without bone grafting showed a significantly greater amount of callus on the side of the fracture further from the fixator (Fig 8.2) This occurred in both the lateral and antero-medial locations.

Complications.

A) Infection.

A pin track infection was defined as a persistent discharge from a pin site from which a positive culture was obtained. In this series 14 patients developed a discharge from one or more pin sites and 12 (25.5%) had a pin track infection. The infecting organisms were *Staphylococcus aureus* (x4), *Staphylococcus albus* (x3), *Escherichia coli* (x2), *Streptococcus* species (x1) and *Enterococci* (x1). Eleven of the pin track infections were successfully treated but in one case deep infection ensued. This will be discussed later.

Deep infection at the fracture site occurred in two cases (4.2%). These were both grade 3 open fractures. One was successfully treated with antibiotics and went on to union but the other required a below knee amputation.



Fig 8.2

As with the rabbit fractures (Fig 6.20) it was common to find callus formation on the cortex further from the fixator. This occurred with both the lateral and anter-medial locations.

B) Pin loosening.

Pin loosening is frequently associated with pin infection although it can also occur if only one bony cortex is penetrated by the transfixion pin or if a patient is particularly active in full weight bearing mobilisation (Fig 8.3). This latter cause is usually associated with a healed fracture. In this series 7 patients (14.9%) had loose pins although only 2 (4.2%) patients required pins to be replaced. Pin loosening was not a clinical problem.

C) Amputations.

Two patients (4.2%) required amputation. One of these was performed on a 23 year old man sixteen months after injury because of deep infection. Further treatment for the bone infection was not instituted because of his co-existing injuries. He had sustained an ipsilateral femoral fracture with two inches of bone loss. The resultant femoral shortening combined with the deep infection encouraged the patient to seek amputation. The second amputation was performed in a 68 year old man 2.5 weeks after admission because of the severity of the other injuries to the leg.

D) Neurological problems.

Two patients (4.2%) developed neurological problems, one developing a lateral popliteal nerve palsy soon after the application of the fixator and the second developing a sural nerve palsy. Both recovered after removal of the fixator. In neither case did the pins seem excessively close to the relevant nerve.

E) Joint stiffness.

Post-operatively all the patients showed a tendency to develop an equinus deformity. This was prevented by the use of either a below knee plaster backslab or preferably by the use of a foot piece which can easily be connected to the Hughes device (Fig 8.4). This footpiece was removed as soon as possible and joint movement encouraged.

Nine patients complained of severe ankle or sub-talar stiffness to the extent that they had to considerably modify their activities and it is of interest that all of these patients had had their fixator applied for less than six weeks and therefore had spent a longer time in a cast. The restriction of joint movement was a subjective impression gained from the patient's history and only those patients who complained of severe problems have been included.

Tibial plafond fracture

One tibial plafond fracture was treated with distraction external fixation or "ligamentotaxis". The patient was a 48 year old man who had had his right foot trapped under falling scaffolding sustaining the injury shown in Figure 8.5. He was treated initially by plaster immobilisation but this failed to control the fracture and a Hughes external fixator was applied five days after admission (Fig 8.6). This was left in place for 3.5 weeks and he was then treated in a walking plaster. The fracture was felt to be clinically united after 11 weeks. Figure 8.7 shows that the overall final position was satisfactory but that the intra-articular comminution was such that an



Fig 8.4

Many patients showed a tendency to develop an equinus deformity post-operatively. This foot-piece was developed to prevent contracture formation. It can also be used as a drop foot splint.



Fig 8.5



Fig 8.6



Fig 8.7

A tibial plafond fracture in a 48 year old man (8.5). The fracture was distracted using a Hughes device (8.6) and a reasonable position obtained although the slight step in the articular surface of the distal tibia seen after reduction was present in the final films (8.7). The patient continues to have pain and stiffness in the ankle.

irregularity persisted in the articular surface. Ten months after the fracture the patient still complained of pain and stiffness in the ankle.

Humeral fractures

Three patients were treated with external fixation following closed humeral mid-shaft fractures associated with radial nerve palsies. In each case a Hughes external fixator was applied to the lateral aspect of the humerus with all four pins placed closely together and the bar at least 6cm from the limb. This biomechanically less stiff configuration led to a greater amount of callus than was seen in the tibial fractures (Fig 8.8). The distribution of the callus was not confined to the cortex opposite the fixator but was more circumferential in distribution (Fig 8.9). The fixators were kept on for 9, 4.5 and 8 weeks and clinically union had occurred at 9, 17 and 12 weeks. There was one pin track infection from which *Staphylococcus aureus* was cultured but no deep infection. The radial nerve palsies had recovered by 6, 8 and 5 months respectively.

Pelvic disruption.

Three symphysis pubis diastases were treated, one of these being associated with a sacro-iliac disruption. In each case an anterior bar was applied with two pins in each iliac crest and it was found to be comparatively easy to close the diastasis.

The gaps in the symphyses on admission, as measured on X-ray, were 48, 21 and 45mm with a 29mm gap being noted in the right sacro-iliac joint in the third patient. Application of the Hughes device using compression resulted in closure of the diastases to 8, 5 and 5mm with



Fig 8.8

The humeral fractures were fixed with the pins close together. This less stiff configuration led to the formation of more callus than seen in the tibiae.

Not only was there more callus but the overall distribution tended to be circumferential.



Fig 8.9

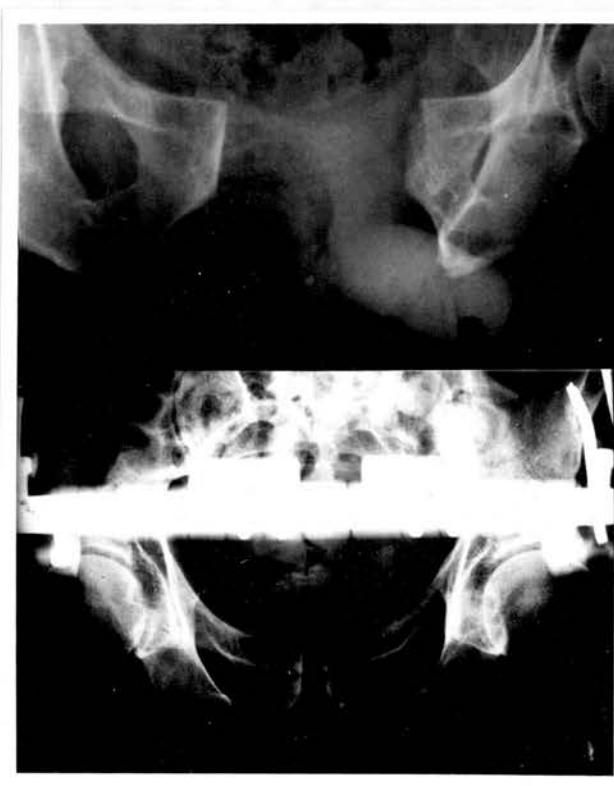


Fig 8.10

Pubic diastases can be closed with a unilateral external fixator such as the Hughes. In this case two transfixion pins have been placed in each iliac crest and a 48mm gap was reduced to 8mm. The diastases all partially recurred after fixator removal.

the sacro-iliac gap being closed to 11mm (Fig 8.10).

The fixators were left in position for 5, 8 and 2 weeks. The device was removed early from the last patient because of failure to control the sacro-iliac joint. He was subsequently treated with a pelvic sling. Internal fixation of the sacro-iliac joint was considered but the patient's considerable obesity was felt to be a contra-indication.

After removal the diastases recurred to an extent in all three cases with the eventual gaps being 22, 10 and 28mm. In the third patient the sacro-iliac joint healed with a gap of 16mm. No patient had symptoms referable to the diastases but the last patient complained of sacro-iliac pain.

No infection was encountered but one patient developed hypoaesthesia in the distribution of his right lateral cutaneous nerve of thigh. This recovered after removal of the fixator.

This limited use of the Hughes fixator for the stabilisation of the pelvis following fracture tends to confirm the view of Tile (1984) that external fixation can only be used as a definitive treatment method if the posterior sacro-iliac ligaments are intact.

External fixation in the treatment of non-union.

The Hughes fixator has been used in eight cases of established non-union. Five of these have been in the tibia and three in the femur. The use in the tibia is detailed in Table 8.16.

The age range was between 22 and 63 years with an average age of 29.4 years. The shortest time prior to treatment was 6.5 months and the longest 10 years. All were bone grafted at the time of external fixation and four of the five went on to union. In two patients the

Age (yr)	Non-union duration (mth)	Type	Fixator duration (wk)	Graft No.	Union time (wk)	Position on tibia
23	16.0	H	22.0	1	22.0	A/medial
25	6.5	A	36.0	1	36.0	Lateral
22	9.0	A	7.0	1	18.0	Lateral
63	15.0	A	9.0	1	26.0	Lateral
34	120.0	H	42.0	1	----	A/medial

Details of the use of the Hughes external
fixator in tibial non-unions.
(H = hypertrophic, A= atrophic).

Table 8.16

fixator was applied for 22 and 36 weeks and the fractures were clinically united when the fixator was removed. Two other patients had the fixator removed earlier at 7 and 9 weeks and they took a further 11 and 17 weeks to unite. In one patient the non-union persisted. This patient had had an infected non-union for 10 years and after excision of infected material, external fixation and bone grafting he absconded from treatment. He returned after 10 months with a persistent non-union and refused further treatment. This was the only infected tibial non-union treated.

The three femoral non-unions are detailed. All were difficult clinical situations successfully treated with the Hughes device. The first patient was a 36 year old man who ten years previously had had a femoral haemangioma excised along with several inches of his lower femoral diaphysis. The bone was autoclaved, returned to the femur and stabilised with a Kuntscher nail (Fig 8.11). He complained of pain related to the proximal end of the nail as well as pain in the distal femur. Removal of the nail confirmed that both ends of the femoral segment were ununited and a Hughes device was applied (Fig 8.12). The area of the segment was bone grafted on two occasions with the result that a bridge of new bone appeared around the avascular segment (Fig 8.13). The femur has united but the patient complains still of knee pain. The fixator was in place for 40 weeks. *Staphylococcus albus* was cultured from the pin sites on two occasions but no problem with infection was encountered over this period.

The second patient was a 23 year old man who sustained a grade 3 compound femoral fracture which had been treated conservatively for three months resulting in an infected non-union. This was treated with excision of dead tissue, external fixation and bone grafting. The fixator was left in position for three months and the fracture was felt to be clinically united two months after its removal. There was discharge from one pin site



A ten year old femoral non-union (8.11). The Hughes device was used (8.12) with bone grafting being performed on two occasions. The avascular segment was eventually bridged by bone (8.13).

Fig 8.11

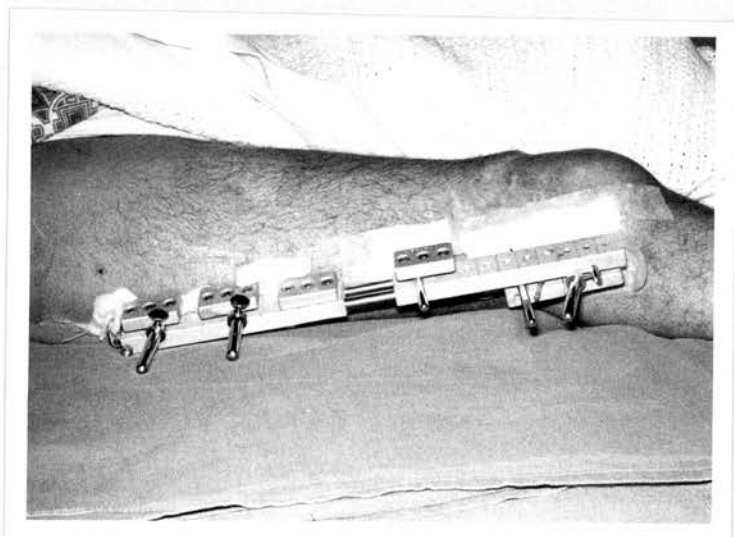


Fig 8.12

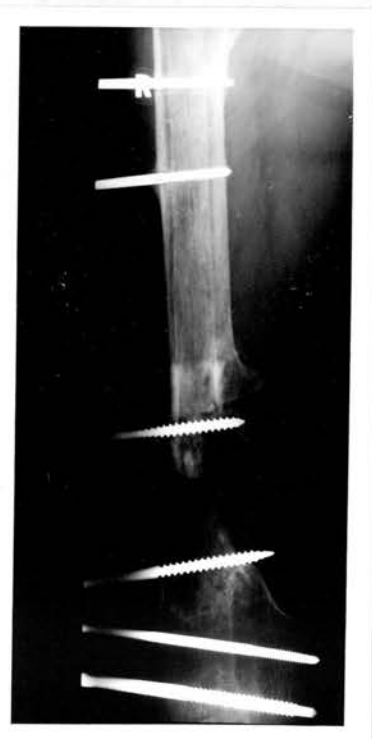


Fig 8.13

but no infection.

The last patient was a 59 year old man who had had a femoral non-union for 16 years without any confirmatory evidence of infection. He had had four previous unsuccessful attempts at internal fixation and bone grafting. A Hughes device was applied in addition to further bone grafting and the use of electrical osteogenic stimulation. The fixator was retained for 26 weeks and clinical union was present at 40 weeks. Three of the pins loosened secondary to infection. *Staphylococcus aureus* and a few *clostridium welchii* were cultured but again no clinically significant infection ensued.

External fixation in osteotomy work.

Five tibial osteotomies were performed. In one case a valgising upper tibial osteotomy was held using two parallel pins in the proximal tibia. Compression was applied and the device kept in place for 7 weeks following which the osteotomy was felt to be clinically united.

A second upper tibial osteotomy was performed for Blount's disease. The fixator was kept in place for 18 weeks with union being obtained at this time. Good knee function was preserved.

Three tibial derotation osteotomies were performed using a smaller Hughes device (Fig 8.14). The fixators were retained for 6, 6 and 5 weeks and then a cast applied (Fig 8.15). In the first two cases union was achieved 6 weeks after removal of the fixator with a satisfactory clinical result. In the third case, however, union was delayed until 24 weeks for no apparent reason. There was no pin discharge or infection in any of these cases.



Fig 8.14



Fig 8.15

Three tibial derotation osteotomies were performed. It was found that a smaller Hughes device was adequate to stabilise these osteotomies (8.14). If the pins were placed close together then a plaster cast could easily be constructed around the pins prior to the fixator being removed under local anaesthetic (8.15).

External fixation in arthrodesis.

Only one arthrodesis was performed in a woman with bilateral knee osteoarthritis. The left knee showed severe changes in all three compartments (Fig 8.16) and was treated by arthrodesis using a Hughes device on the anterior surface (Fig 8.17). Compression was applied. The fixator was removed after 6 weeks following which there was a small amount of movement at the arthrodesis. The fusion was clinically solid 15 weeks after surgery. On one occasion there was a pin discharge from which no organisms were cultured.

Discussion.

The preceding results suggest that the time to bone union and the residual deformity are most affected by the initial reduction and the length of time for which the fixator is applied. The other parameters of pin angle, pin location, effective pin length and fixator location do not seem to play a major role. This is corroborated by the observation that the reduced position of every fracture, non-union and osteotomy was maintained while the fixator was in position suggesting that every clinically useful configuration of the device was stiff enough to hold the bone fragments. Table 8.15 shows that of the 17 mal-unions, 11 were mal-reduced initially. The initial mal-reduction was usually very similar to the end result no matter what attempts had been made to correct the deformity during the period of treatment. The importance of the initial reduction and the duration of fixation is emphasized by examining some of the fractures most at risk of non-union - the lower third tibial



Fig 8.16



Fig 8.17

A knee arthrodesis was performed in a patient with three compartment osteoarthritis (8.16). The Hughes fixator held the osteotomy under compression for six weeks (8.17) and clinical union was present after a further nine weeks.

fractures (Table 8.11). Five of these fractures were virtually identical low tibial fractures. Figure 8.18 shows a patient who had a good reduction carried out and the fixator left in position for 17 weeks at which time the fracture was clinically solid although a cast was applied for a further four weeks after removal of the fixator. The result is obviously good (Fig 8.19). In contrast to this Fig 8.20 shows a patient who had a mal-reduction where varus, displacement, bone shortening and a recurvatum deformity of the fibula were created by the surgeon. The fixator was removed at three weeks resulting in an increasing varus position and the formation of a tibial recurvatum deformity secondary to the fibular deformity (Fig 8.21). The fracture eventually healed after plating and grafting and although the varus was corrected at this operation the recurvatum deformity persisted. Two similar fractures were also treated with fixators being applied for 5 and 4 weeks following initial mal-reductions. The deformities again increased after fixator removal. A fifth patient whose fixator was kept on for eight weeks following a mal-reduction healed in the identical mal-reduced position without grafting. It is therefore clear that to avoid residual deformity a good reduction is essential and the fixator should be left in position for at least 6 weeks. If a bone gap is unavoidable then consideration should be given to early bone grafting to create the necessary conditions for union.

The major contribution to the mal-union rate of 38.6% was therefore poor surgical technique and it should be emphasized that despite the seeming simplicity of the Hughes and other similar devices it is their unilateral design that puts considerable demands on the surgeon. Complex devices such as the Hoffmann are more forgiving as the universal joints can be altered to change fracture reduction if necessary. Without universal joints pin placement must be extremely accurate as any attempt to force a change in fracture position after pin placement



Fig 8.18



Fig 8.19

A compound lower tibial fracture treated with the Hughes fixator. Fig 8.18 shows that a good reduction was obtained. The fixator was left in position for 17 weeks the fracture being clinically united at the time of fixator removal (8.19). The end result was satisfactory.



Fig 8.20



Fig 8.21

A compound lower tibial fracture treated with the Hughes fixator. Fig 8.20 shows that a poor reduction has been obtained. The lower bone fragment is in varus and displacement and shortening are present. The fixator was left in position for three weeks and the fracture was subsequently treated with a cast. Fig 8.21 shows that in addition to the increased varus deformity the tibia has followed the fibula into recurvatum. This is obviously an unsatisfactory result.

will be associated with mal-union. It is clear that closed reduction of a fracture after the percutaneous placement of a unilateral fixator is virtually impossible. These obvious drawbacks of the Hughes fixator must be counter-balanced by the increased access to soft tissue which it permits.

The time to bone union depends on several factors such as the bone involved, the location of the fracture within the bone and the extent of the soft tissue damage. Therefore the use of an arbitrary time beyond which, if healing has not occurred, delayed or non-union is said to be present would seem to be invalid and in fact the non-union rates of different series depend mainly on the author's definition of what constitutes a non-union. Tibial non-union has been said to be predictable at 12 weeks (Souter 1968), at 20 weeks (Ellis, 1958; Nicoll, 1964), at 6 months (Thonold, 1975; Karlstrom and Olerud, 1975) and at one year (Velazco et al, 1983). The tendency recently has been for surgeons to anticipate rather than to wait for non-union and to bone graft earlier to minimize the time to union. This principle was usually adopted in this series and therefore the non-union rate will not be discussed but rather the time to final clinical union will be taken as the important clinical parameter. Clinical union rather than radiological union was chosen because it is clinical union which is of paramount importance to the patient. Radiological union is often difficult to determine and frequently only acted on in conjunction with clinical examination.

The grade 3 open tibial fractures united at an average of 44.5 weeks. This compares well with 34 weeks reported by Karlstrom and Olerud (1975) and 41 weeks by Krempen et al (1979) using the Hoffmann device. These series despite reporting on the treatment of severe tibial fractures were not specific as to fracture grading. However Lawyer and Lubbers (1980), again using the Hoffmann, reported on bone union for the different grades of tibial fracture. Their grade 3 open fractures united in an average of 39

weeks while their grade 2 fractures took an average of 20 weeks, the grade 1 fractures 21 weeks and the closed fractures 23 weeks. They further commented that anatomical reduction reduced the time to union in the closed fractures to an average of 19 weeks whereas the mal-reduced closed fractures took an average of 29.5 weeks to heal.

Ellis (1958) reported that his severe tibial fractures which were treated conservatively took an average of 27 weeks to unite and Hutchins (1981) reviewing the Edinburgh experience of severe tibial fractures treated by various methods reported an average healing time of 25 weeks.

Good results in the treatment of grade 3 open tibial fractures have also been reported using other treatment methods. Velazco et al (1983) report a 16% delayed union rate using the Lottes nail and Harvey et al (1975) reported that they only had to bone graft 6.6% of their severe tibial fractures initially treated with a Hodgkinson nail. Both Burwell (1971) and Olerud and Karlstrom (1972) had a 4.4% non-union rate after plating a group of fractures. Unfortunately many of the results in the literature are not comparable with the results of this series. The older fracture grading method employed by Ellis (1958) and Hutchins (1981) was based more on the extent of the bone damage rather than the soft tissue damage and although these are often related many of the injuries formerly classified as severe tibial fractures might not now be classified as Grade 3 tibial fractures. Amputation rates in more modern series are lower than in the older series suggesting that surgeons are now attempting to treat fractures that formerly were considered too bad to treat. Such fractures would be expected to have a prolonged union time. A further problem is that the currently employed fracture grades cover a broad spectrum of fractures and while many severe tibial fractures are easily classified as grade 3 the classification of other less severe fractures is more

subjective. An example of this is to be seen in the work of Velazco et al (1983) who used intra-medullary nailing to treat transverse grade 3 fractures but the Hoffmann to treat less stable grade 3 tibial fractures. It is likely that some of his stable grade 3 fractures might well be grade 2 fractures carrying a better prognosis.

In this series the grade 2 fractures united in an average of 26.7 weeks with only 28% requiring bone grafting. Again comparison with older series is difficult but Ellis (1958) said that his conservatively treated, moderately severe tibial fractures healed in an average of 15 weeks. The externally fixed grade 2 fractures reported by Lawyer and Lubbers (1979) took an average of 20 weeks to unite but they only treated three patients. Clancey and Hansen (1978) reported a 40% delayed union rate in grade 2 fractures treated with the Roger Anderson device.

Table 8.8 shows that the time to union of grade 2 tibial fractures in this series is dependent on a good initial reduction and a prolonged fixator application. Under these conditions the time to union was 18.3 weeks. This figure compares well with those of Ellis and Lawyer and Lubbers who also stressed the need for accurate reduction.

The disturbing results in this series are those for the closed and grade 1 open tibial fractures where the average time to union is 29.2 weeks. As the union times for these fractures are more easily compared with older series it is clear that the union times are unacceptable. Ellis (1958) showed that minor degrees of compound wounding had no demonstrable effect on the speed of union and in his series the average time to union of this type of fracture was 10 weeks. More recent work by Sarmiento (1967) has shown that on average a closed tibial fracture will unite in 13.6 weeks if treated conservatively by functional bracing. The average union time for grade 1 fractures was 16.7 weeks. Digby and Holloway (1982) also showed an average union time of 16 weeks for

conservatively treated closed or grade 1 tibial fractures.

It is interesting that the union times for closed and grade 1 open tibial fractures were not just prolonged but were actually 2.5 weeks longer on average than the union times for the grade 2 fractures. Lawyer and Lubbers (1979) also reported this increased union time in their simpler fractures. These apparently poor results need further analysis.

Of the 11 closed and grade 1 fractures 5 were externally fixed because fasciotomies were performed as treatment for compartment syndrome. Two were fixed because of failure of initial conservative management and 2 were primarily fixed as treatment for short oblique tibial fractures. One was externally fixed because of the segmental nature of the fracture and 1 because of associated tetraplegia following a cervical fracture.

The effect that compartment syndrome might have on union time is unknown although it is interesting to note that Ellis (1958) in his paper on ischaemic contracture, reports delayed union in four of his nine patients (44.4%). Karlstrom et al (1975) reported on 23 patients with compartment syndrome following tibial fracture and stated that 15 (65.2%) had delayed or non-union. In this series the average time to union for the 5 patients that developed compartment syndrome was 27.4 weeks. Sheridan and Martin (1976) have shown that if fasciotomy is delayed more than 12 hours after the onset of compartment syndrome symptoms then the soft tissue damage is such that only 8% of patients have normal ankle function. This suggests that the degree of soft tissue damage in compartment syndrome may be sufficient to interfere with bone blood flow and thereby bone union. This theory is untested and needs further investigation. Three of the patients who had fasciotomies performed required later bone grafting and Fig 8.22 illustrates why this was the case. The antero-posterior X-rays of the three patients are shown and it is obvious that a mal-reduction is

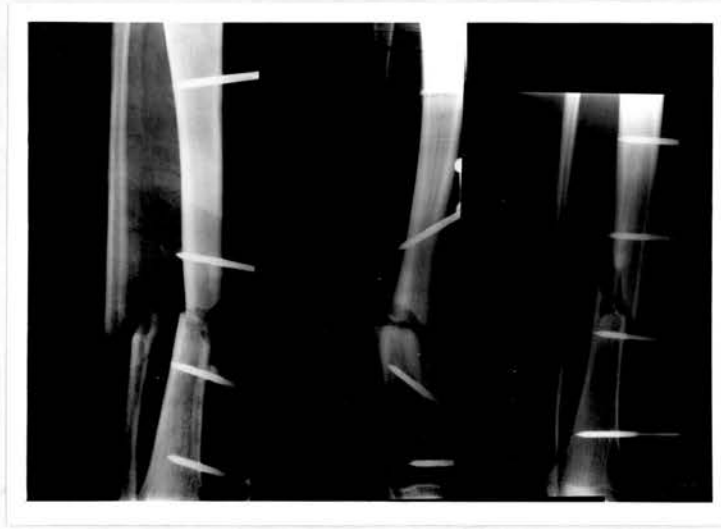


Fig 8.22

Three patients who had fasciotomies performed required subsequent bone grafting. The antero-posterior X-rays of these patients are shown. In none of the cases was an adequate reduction obtained.

present in each case.

Of the 2 patients who had their closed tibial fractures externally fixed because of failure of conservative management 1 had an excellent reduction and healed in 12 weeks. The other, however, had a poor reduction (Fig 8.23) and required bone grafting before the fracture healed at one year.

The 2 patients who were primarily fixed because of the obliquity of the fracture both had grade 1 fractures but they had different results. Both were reduced well and in both cases the fixator was kept on for 6 weeks. One fracture healed in 18 weeks but the other slipped after the fixator was removed and took 1 year to heal. The patient with the closed segmental fracture had a good initial reduction but was bone grafted at 13 weeks at which time it was noted that much of the segment was avascular. The fracture has not yet healed after 40 weeks. It would seem that the closed grading of the fracture belies its severity and that the soft tissue damage around the bone segment was considerable. The last fracture was also a closed segmental fracture in a patient with tetraplegia. A good reduction was obtained and union was evident at 21 weeks.

These 11 patients do not therefore represent a typical cross-section of minor tibial fractures. The presence of compartment syndrome in 5 and segmental fractures in 2 suggests more soft tissue damage than occurs usually in these fractures. Of the remaining 4 fractures 1 was mal-reduced. Lawyer and Lubbers do not detail why they used external fixation on their closed or grade 1 fractures but it may be that they also were treating fairly severe clinical problems.

Burney (1979), using the unilateral Hoffmann device with a low biomechanical stiffness, states that closed and grade 1 fractures made up 22.4% and 21.2% of his series. Unfortunately he does not give the union times of the individual gradings.

Pin track infection occurred in 12 patients (25.5%).



Fig 8.23

A lateral X-ray of a patient who was treated with external fixation because of failure of conservative management. The mal-reduction, using a fixation method which minimizes callus formation, will increase the chance of non-union.

This is usually a minor problem which responds to removal of the pin supplemented, if indicated, by systemic antibiotics. However pin track infection can lead to deep infection in two instances. Firstly as shown in Fig 8.24 where the pin is inserted through a fracture site, spread of infection may cause infection at the fracture. In this case the infection risk was increased by the loose placement of the pin which was placed in a separate bone fragment. Secondly if intra-medullary nailing is employed after the removal of external fixation, deep infection can ensue if the products of a pin track infection are spread in the medullary canal (Karlstrom and Olerud, 1975). In other circumstances pin track infection is relatively unimportant. Benum and Svehnijsen (1982) have reported a 50% pin track infection rate using the Hoffmann without any deep infection. Berhens (1982) reported a 7.5% pin track infection rate using the AO device with its thicker pins without any deep infection. Velazco et al (1983) had an 80% pin track infection rate but they did not pre-drill the bone prior to the introduction of the Hoffmann pins. This resulted in a 12.5% ring sequestrum rate.

Pin loosening is sometimes associated with pin infection although incorrect pin application and over zealous mobilisation may also cause this (Fig 8.3). In this series pin loosening was a minor problem with no long-term sequelae. There were no pin breakages as mentioned by Burney (1979) with the Hoffmann device.

The control of pin track sepsis is achieved by good surgical technique. In addition to pre-drilling the pin track and placing the pin correctly in both bony cortices it was found necessary to incise widely the soft tissues around the pin and to repeat this as necessary for the first three to four weeks. The need for this is also emphasized by Green (1981). Burney (1979) has stated that the pin track infection rate increases with time. This was not found to be the case in this series as infections were rare after four weeks.



Fig 8.24

Deep infection can be caused by incorrect pin placement. In this case the second pin has been placed in a loose bone fragment. The resulting pin loosening caused pin track sepsis initially followed by deep sepsis.

The size and component material of the pins affects both pin loosening and infection rate. The stiffness of the pins increases with the fourth power of the radius and the Young's Modulus of the material. Thus the thinner and the less stiff the pin the higher the rate of infection. The Hoffmann device uses 3 mm pins made of stainless steel and is associated with higher infection rates (Benum and Svenningsen, 1982) than the 5mm Schanz screws of the AO device (Behrens, 1982) which are also made of stainless steel. The transfixion pins for the Hughes device are similar in size to the Schanz screws at 4.8mm but are made of titanium which has a lower Young's Modulus than stainless steel and is consequently less stiff.

The overall deep infection rate in this series was 4.2% with the two patients both having grade 3 fractures. One of the cases might have been avoided if better surgical technique had been used. As deep infection is a major clinical problem it is important to compare the infection rate with those recorded for other external fixation devices and with other treatment methods. Unfortunately accurate comparison is often difficult because other authors use different fracture grading systems or do not specify which type of fracture they are referring to. Table 8.17 shows the deep infection results for other external fixation series as well as for other methods of fracture management. The figures refer to the overall infection rates in the series.

Both conservative management and internal fixation using plates tend to be associated with deep infection rates in the range of 10 - 15%. Table 18.7 demonstrates that external fixation lowers the infection rate usually to the 2 - 8% area. It is interesting that Edge and Denham (1981) had a high deep infection rate of 30%. Their device is biomechanically weak (Campbell and Kempson, 1979) and provides insufficient fixation compared with other devices. The use of such a device in the presence of severe soft tissue injury may well

<u>Treatment method</u>	<u>Author/year</u>	<u>Infection rate</u>
Plaster	Nicoll (1964)	15.3%
Plaster	Hughes (1983)	10.0%
Pins and Plaster	Anderson (1974)	8.3%
<u>Internal fixation</u>		
Plating	Lottes (1952)	35.0%
Intra-medullary nail	Lottes (1957)	8.0%
Plating	Burwell (1971)	14.0%
Plating	Olerud (1972)	25.0%
<u>External fixation</u>		
Hoffmann	Karlstrom (1975)	0.0%
Hoffmann	Krempen (1979)	3.0%
Hoffmann	Burney (1979)	5.3%
Portsmouth	Edge (1981)	30.0%
Hoffmann	Ramadier (1981)	8.4%
Hoffmann	Benum (1982)	2.0%
Hughes	Court-Brown (1983)	4.2%

The overall infection rates for all grades of fractures in other series treated by alternative methods or with other external fixators.

Table 8.17

account for this result.

The Hughes device with a stiffness comparable to a Hoffmann-Vidal double frame and with the relatively stiff transfixion pins is associated with a low deep infection rate.

The rate of neurological problems is low at 4.2% and the same as that recorded by Benum and Svehnigsen (1982). The subjective severe joint stiffness complained of by 9 patients was probably associated with the degree of the soft tissue damage and the length of time in plaster after the removal of the device. As with other rigid fixation methods the Hughes fixator permits full joint mobilisation.

The Hughes device has rarely been used in locations other than the tibial diaphysis. The one tibial plafond fracture that was treated did moderately well and the overall alignment of the joint was retained although other fixation methods may have been superior. The three humeral fractures all healed well but the muscle transfixion that is required in the application of an external fixator in this situation seems unjustified unless there is severe soft tissue damage.

In the pelvis the Hughes device, like other unilateral fixators, can only be used to close a pubic diastasis. More complex fractures or dislocations demand more sophisticated devices such as the Hoffmann or the AO fixators. If a pubic diastasis is to be treated the bar should be left in place for a minimum of 8 weeks or significant recurrence of the deformity may ensue.

Of the eight non-unions treated with the Hughes external fixator seven went on to unite. Only one of the two infected non-unions united. However as all of the non-unions were bone grafted and subjected to variable compression at the time of external fixation it is difficult to identify which factor is mainly responsible for union.

The major role of cortico-cancellous bone grafting from the ilium, as used in this series, is undeniable.

Phemister (1947) demonstrated that non-unions could be treated successfully by bone grafting without resecting the pseudarthrosis. Souter (1969) confirmed the success of using cancellous strip grafts from the iliac crest in the management of long bone non-unions.

Danis (1949), however, showed that some non-unions could unite without bone grafting and following this it has become apparent that the alteration of the biomechanical environment is enough to stimulate union in some non-unions. Judet and Judet (1960) then differentiated non-unions into hypertrophic and atrophic. Kuntscher (1962) showed that the use of a wide intramedullary nail with weight bearing would cause non-unions to heal without grafting. Trueta (1965) reported on a tibial non-union which healed after the introduction of two compressive bone screws at 90 degrees to the fracture.

Muller (1966) showed that hypertrophic non-unions could be stimulated to unite by compressive plating alone. He stated that a graft was only required for atrophic non-union or if the non-union was taken down to correct a rotational deformity or if the gap was large. Using these principles Muller and Thomas (1979) described the treatment of 28 hypertrophic non-unions of the tibia in which 10 of the patients were bone grafted in addition to compressive plating being carried out. Two deep infections occurred and two of the operations failed.

Recently Basset (1977) has examined the role of pulsing magnetic fields in the treatment of non-unions and claims a 76% success rate in stimulating union in acquired pseudarthroses with previously unsuccessful treatment. He further claims that hypertrophic non-unions remodel using this treatment. In his later research (1981) he has claimed an 87% success rate in non-union treatment.

The Hoffmann device has been used extensively in the treatment of both hypertrophic and atrophic non-unions. Krempen et al (1979) treated 23 infected and uninfected

non-unions with the Hoffmann and bone grafting. Good or acceptable results were obtained in 21 patients.

Vidal et al (1979) reported that the average time to union for infected, atrophic non-unions treated with the Hoffmann device and bone grafting was 10 months. Hedley and Bernstein (1983) have reported on the treatment of 22 non-unions treated with the Hoffmann. Fourteen of these cases were infected and the average elapsed time before treatment was 17 months. Twenty-one of the fractures united. The uninfected non-unions were treated with external fixation for an average of 12.5 weeks with union occurring after an average of 7.5 months. Two of these patients were bone grafted at the time of surgery but a further two hypertrophic non-unions healed without grafting. Ordway (1982) has also reported this phenomenon.

Hedley and Bernstein had pin track problems in 41% of their patients including pin loosening and discharge. There was however no pin track or deep infection.

From the above results it would seem that uninfected non-unions can be expected to unite no matter what conventional treatment is used and that hypertrophic non-unions do not require bone grafting as much as an alteration in their biomechanical environment whether this be achieved by external or internal fixation.

As with the open fractures the time to union of tibial non-unions is longer in recent reports than in the older literature. Souter (1969) comments that cancellous strip grafting should stimulate union in 16 to 20 weeks. However Rosen (1979) using internal fixation reports healing times of 26 weeks if the pseudarthrosis is not excised and 39 weeks if it is. Hedley and Bernstein (1983) had an average union time of 32.5 weeks for their uninfected non-unions. In this series the uninfected non-unions united in an average 25.5 weeks which compares well with previous reports of internal and external fixation. As with other external fixation series there were no infections in the previously uninfected non-

unions in this series. In contrast Muller and Thomas (1979) reported a 7.1% infection rate and Rosen (1979) a 25% infection rate in previously uninfected non-unions treated by plating. Souter (1969) encountered a 3.9% infection rate but felt that this was mainly due to prior occult infection in the bone.

External skeletal fixation would seem to have a role in the treatment of established uninfected non-union because of the low infection rate associated with its use and the ease of removal of the device. There would seem to be a particular use in hypertrophic non-unions where a percutaneous application of a fixator with compression may well be successful.

The three femoral atrophic non-unions united in an average of 14 months. These were all difficult clinical problems and it is considered that the stability provided by the Hughes facilitated union but it is accepted that other treatment methods might have been successful.

Of the two patients with infected non-unions one went on to union but the other was unreliable and defaulted from treatment. Although very few infected non-unions have been treated in this series these difficult clinical problems are best treated using external fixation to provide the necessary rigidity to allow union to occur. Although good results are obtainable with internal fixation the low infection rates associated with external fixation make it the treatment of choice.

The role of external fixation in the stabilisation of osteotomies is essentially unknown. Southwick (1967) used external fixation to hold the proximal femur following his osteotomy for slipped upper femoral epiphysis and Olerud (1979) has used the Hoffmann to stabilise pelvic osteotomies. The three tibial rotational osteotomies in this series were successfully treated with external fixation although union was delayed in one case. Although other fixation methods can be used the theoretical advantages of external fixation are its lower infection rate and the precision with which the correction angle

can be estimated by appropriate pin placement.

Similarly the two upper tibial osteotomies were successful but other treatment methods exist which are probably easier to manage in this situation. However experience in the use of the Hughes in this situation may well help in dealing with unusual situations.

External fixation in arthrodesis is widely accepted following the work of Charnley (1953). The fact that one knee arthrodesis was successful does not fully validate the use of the Hughes in this situation but it is likely that the device does confer adequate stability and compression to ensure fusion. It is unlikely however that it would be of value in the arthrodesis of joints such as the hip, elbow and shoulder where, if external fixation was desired, a device capable of multi-planar fixation such as a Hoffmann would be required (Mears, 1979).

SECTION 3

CHAPTER 3

The Current and Future Use of
External Fixation.

The preceding clinical work indicates that the Hughes external fixator can be used to stabilise long bone diaphyseal and metaphyseal fractures and non-unions. Clinically all the fixator configurations used were successful in holding the bone fragments in the position dictated by the surgeon. There were two situations where an attempted use of the Hughes in a long bone fracture was unsuccessful and a Hoffmann device was required. Firstly where there are multiple, widely separated fractures in a long bone the length of the bar is insufficient to hold both fractures adequately (Fig 8.25) and secondly where both ends of a segmental fracture are transverse and therefore difficult to reduce and hold while the Hughes is applied (Fig 8.26). In all other long bone fractures the Hughes has been satisfactory.

The device has a limited role in the treatment of pelvic fractures. It can successfully hold a reduced pubic diastasis but any more complex pelvic problem requires the use of a fixator which can be built into a three-dimensional frame.

The fact that external skeletal fixation alters bone healing is indisputable. The results of the animal work indicate that external fixation diminishes the periosteal response but enhances the endochondral ossification of the callus that is formed. It also accelerates medullary ossification, this being evident not just by the increased medullary response but in the degree of cortical osteoporosis produced by enlargement of the medullary vessels traversing the cortex. This alteration in the periosteal/medullary response has been previously noted following internal fixation using plates (Olerud and Dankwardt-Lillestrom, 1971). The common factor in these two types of fixation is the rigidity with which the fractures are held. A high degree of stiffness lessens the periosteal callus response (Yamagishi and Yoshimura, 1955). This fact is further illustrated in



Fig 8.25

Not all fractures of the tibia are suitable for external fixation with a Hughes device. These X-rays show a fracture in the upper tibial metaphysis along with a lower third segmental fracture. The overall distance between the fractures meant that a Hoffmann had to be used. The configuration used to stabilise these fractures is shown in Fig 1.4.

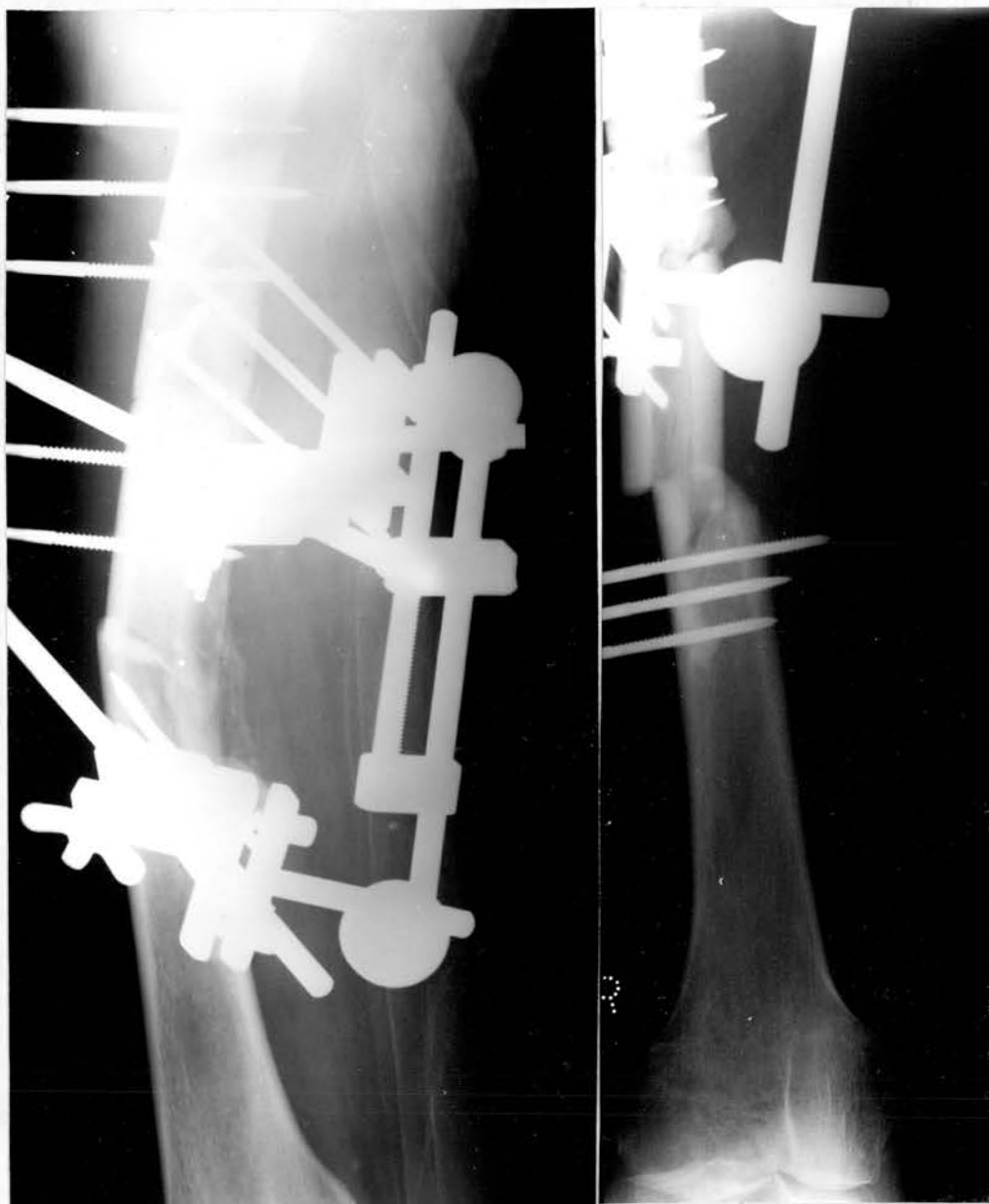


Fig 8.26

The transverse nature of both fractures in the femur made reduction prior to the application of a Hughes fixator impossible. Accordingly a Hoffmann was used but even with this device a full reduction of the lower fracture has not been obtained.

both the animal and clinical work by noting the increased callus response on the less stiff cortex further from the fixator (Figs 6.20 and 8.2).

The need for callus in bone healing is at the core of all the arguments for and against rigid internal fixation of fractures. Although the AO group have followed Danis's arguments (1949) that callus production is undesirable McKibben (1978) has suggested that the inhibition of callus production should not be considered lightly as it is the quickest way to restore the strength of a fractured diaphysis. This is of particular importance if there is a gap in the fracture due either to imperfect reduction or bone loss.

In addition to its effect on fracture healing rigid fixation, whether internal or external, also affects the soft tissue healing. Rhineland and Wilson (1982) have shown that capillary ingrowth in healing bone is facilitated by tissue stability and it is likely that this is true also of soft tissue. Impaired soft tissue healing may well lead to superficial followed by deep infection and the relatively high infection rates (Fig 8.17) that follow conservative management of severe tibial fractures may well be caused by poor stabilisation of the soft tissues.

The initial application of the stiffest configuration of the Hughes external fixator, as indicated in Section 1, chapter 4, is therefore recommended as this will best stabilise the soft tissues. Once these have healed the stiffness of fixation can be reduced by moving the bar away from the limb as shown in Fig 4.4.

The clinical results suggest that if the bar is removed at the time of soft tissue healing, this commonly being between three and four weeks in the grade 1 and 2 open tibial fractures, then there is a high incidence of fracture redisplacement. Table 8.8 suggests that maintenance of the fixator for at least six weeks after a good reduction leads to the shortest average union time with the minimum number of bone grafting procedures.

The application of the results of the animal work to this clinical observation means that in an externally fixed tibia there is an insufficient amount of both periosteal and medullary ossified callus to hold the fracture until about six weeks. If the fixator is removed at this time then usually the stabilisation obtained is adequate to maintain fracture alignment against the deforming forces of muscle pull and gravity. However if the external fixator is retained union will proceed by secondary means without significant callus formation. The diminished callus formation means that fracture gaps will not be bridged and therefore reduction must be good. If a fracture gap is present consideration should be given to early bone grafting to facilitate union.

It would therefore seem that the pessimistic attitude of Gustilo (1982) that external fixation causes non-union is incorrect. However it is only fair to say that the potential for non-union exists if the effect that external skeletal fixation has on bone healing is not understood.

The future of external fixation

There has been considerable interest recently in the stiffness of fracture fixation and several workers have explored the effect of using plates of lower stiffness than those advocated by the AO group (Bradley et al, 1979; Uhthoff et al, 1981; Tayton et al, 1982). These plates have either been made of metals, such as titanium, with a lower Young's modulus than stainless steel (Uhthoff et al, 1981) or of other materials like carbon fibre reinforced plastic (Tayton et al, 1982) or glass epoxy resins (Bradley et al, 1979). There is no doubt that the use of plates of lower stiffness encourages the formation of callus but it is interesting that the only clinical trial carried out using carbon fibre reinforced plates to internally fix human tibial fractures was

associated with a 15% deep infection rate, probably as a result of the low stiffness of fixation.

Unlike internal fixation, external fixation provides conditions where the stiffness of fracture fixation can be varied. This is of particular use in fractures associated with soft tissue loss or damage as the stiffness of fixation can be reduced once the soft tissues have healed.

External fixation will continue to have a significant place in fracture treatment because of its versatility. In addition to its obvious use in compound fractures it may well become a popular method of treating closed fractures providing that the fixator can be applied, and the fracture reduced, by closed means. Therefore although the Hughes external fixator represents an advance on the older fixators in terms of its relative simplicity, low cost and the ease with which fracture stiffness can be varied the difficulty of reducing and holding a fracture without exposing the bone detracts from its usefulness.

Future external fixators suitable for the stabilisation of diaphyseal fractures should be unilateral for reasons of soft tissue access and weight of fixation but they should allow for closed application and fracture reduction. In addition they should permit axial compression at the fracture site to simulate the cyclical loading that occurs in normal gait and which has been shown to facilitate fracture union (Sarmiento, 1977). This might be achieved by incorporating a spring within the device of a strength which permitted some compressive loading but prevented axial displacement of the fracture. The recent publication by De Bastiani et al (1984) describing the dynamic axial fixator devised in Verona has described such a device. Axial compression is gained by an internal spring but unfortunately this occupies a considerable proportion of the fixator thereby allowing a limited range of pin placements. As this was one of the criticisms of the Wagner device which led to the development of the Hughes fixator it is clear that

the dynamic axial fixator does not solve all the problems. What is necessary is a cylindrical device within which a spring can be installed but the pin clamps should be mounted on the outside of the frame to permit variation of pin fixation.

Modern plastics might well reduce the weight of fixators without interfering with stiffness of fracture fixation. Although it is tempting to suppose that the use of plastics might reduce costs it is likely that commercial considerations would prevent this.

The transfixion pins should ideally be made of a non-corrosive metal with a high Young's modulus. The diameter of the pin is not crucial but given modern materials such as stainless steel satisfactory results are gained when pins of 5 - 6mm are used.

REFERENCES

Adrey J (1970) Le Fixateur externe d'Hoffmann couple en cadre. Etude biomechanique dans les Fractures des Jambe. Editions Gead, Paris

Akeson WH, Woo SL-Y, Rutherford L, Coutts RD, Gonsalves M, Amiel, D (1976) The effects of rigidity of internal fixation on long bone remodelling. Acta Scand Orthop 47: 241-9

Allgower M (1956) The Cellular Basis of Wound Repair. Charles C. Thomas, Springfield Illinois

Allgower M, Ruedi T, Kolbow H (1975) Erfahrungen mit der dynamischen Kompressionsplatte (DCP) bei 418 frischen Unterschenkelhalsfrakturen. Arch Orthop Unfall-Chir 82: 247-56

Anderson LD, Hutchins WC, Wright PE (1974) Fractures of the tibia and fibula treated by casts and transfixing pins. Clin Orthop 105: 179-91

Anderson R (1936) An ambulatory method of treating fractures of the shaft of the femur. Surg Gynecol Obstet 62: 865-73

Archie JP, Fixler DE, Ulliyot DJ, Hoffman JIE, Utley JR, Carlson, EL (1973) Measurement of Cardiac Output with Organ Trapping of Radioactive Microspheres. J Appl Physiol 35: 148-54

Aron JD (1976) Using Methylmethacrylate to Make External Fixation Splints. J Bone Joint Surg 58A: 151

Asche G, Haas HG, Klemm K (1979) The External Mini-Fixator: Applications and Indications in Hand Surgery. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 105-12

Basset CAL, Pilla AA, Pawluk RJ (1977) A Non-operative Salvage of Surgically-Resistant Pseudarthroses and Non-unions by Pulsing Electromagnetic Fields. A Preliminary Report. Clin Orthop 124: 128-43

Basset CAL, Mitchell SN, Gaston SR (1981) Treatment of Ununited Tibial Diaphyseal Fractures with Pulsing Electromagnetic Fields. J Bone Joint Surg 63A: 511-23

Behrens F (1982) Unilateral External Fixation for Severe Lower Extremity Lesions: Experience with the ASIF (AO) Tubular Frame. In: D Seligson, Pope M (eds) Concepts in External Fixation. Grune and Stratton, New York, pp 279-92

Benum P, Svehnigsen S (1982) Tibial fractures treated with Hoffmann's external fixation. Acta Orthop Scand 53: 471-6

Berenger-Feraud J-L (1870) Traite de L'immobilisation Directe des Fragments Osseux dans les Fractures. Delahaye, Paris

Boever P (1931) Fixateur automatique pour fractures diaphysaires. J Chir(Brux) 30: 82-90

Boltze WH, Chiquet C, Niederer PG (1978) Der Fixateur Externe (Rohrsystem) Stabilitatsprufung. AO Bulletin, Bern

Bosworth DM (1938) Skeletal distraction of the tibia. Surg Gynecol Obstet 66: 912-24

Braden TD, Brinker WO, Little RW, Jenkins RB, Butler D (1973) Comparative Biomechanical Evaluation of Bone Healing in the Dog. J Amer Vet Med Assn 163: 65-9

Bradford C, Wilson P (1942) Mechanical skeletal fixation in war surgery: Report of sixty-one cases. Surg Gynecol Obstet 75: 468-76

Bradley GW, McKenna GB, Dunn HK, Daniels AV, Statton WO (1979) Effects of Flexural Rigidity of Plates on Bone Healing. J Bone Joint Surg 61A: 866-72

Branemark PI (1959) Vital Microscopy of Bone Marrow in Rabbit. Scand J Clin Lab Invest 11: Suppl 38, 5-82

Braune W, Fischer O (1889) Über den Schwerpunkt des Menschlichen Körpers mit Rücksicht auf die Ausrüstung des deutschen Infanteristen. ABH DK Sachs Ges d Wiss Leipz 15

Brighton CT, Krebs AG (1972) Oxygen Tension of Healing Fractures in the Rabbit. J Bone Joint Surg 54A: 323-32

Brooker AF (1979) The Use of External Fixation in the Treatment of Burn Patients with Fractures. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 225-40

Brookes M (1958) The Vascularisation of Long Bones in the Human Foetus. J Anat 92: 261-7

Brookes M (1971) The Blood Supply of Bone. Butterworths, London

Brookes M, Harrison RG (1957) The Vascularisation of the Rabbit Femur and Tibia. J Anat 91: 61-72

Burney FL (1979) Elastic External Fixation of Tibial Fractures: Study of 1421 cases. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 55-74

Burney FL, Bourgois R (1965) Etude biomechanique de l'osteotaxis. In: La fixation externe en chirurgie. Imp Medicale et Scientifique Bruxelles

Burney FL, Bourgois R, Donkerwolcke M (1982) Elastic External Fixation: A Biomechanical Study of the Half-Frame. In: D Seligson, M Pope (eds) Current Concepts in External Fixation. Grune and Stratton, New York pp 67-78

Burney FL, Rasquin C (1983) The 'Papineau Technique' using Hoffmann External Fixation. In: BT O'Connor, CE Ackroyd, PF de Bruyn (eds) The Severely Injured Limb. Churchill Livingstone, Edinburgh, pp 241-9

Burri C (1983) General Principles for Treatment of Osteomyelitis. In: BT O'Connor, CE Ackroyd, PF de Bruyn (eds) The Severely Injured Limb. Churchill Livingstone, Edinburgh, pp 229-40

Burstein AH, Frankel VH (1971) A standard test for laboratory animal bone. J.Biomech 4: 155-8

Burwell HN (1971) Plate Fixation of Tibial Shaft Fractures. A Survey of 181 Injuries. J Bone Joint Surg 53B: 258-71

Camitz H, Holmgren H, Johansson H (1934) Contribution a l'etude de la nature de la transplantation osseuse. Acta Chir Scand 75: 1-67

Campbell D, Kempson GE (1980) Which External Fixation Device? Injury 12: 291-6

Canalis EM, Hintz RL, Dietrich JW, Maina DM, Raisz LG (1977) Effect of somatomedin and growth hormone on bone collagen synthesis in vitro. Metabolism 26: 1079-87

Carter DR (1978) Anisotropic analysis of strain rosette information from cortical bone. J Biomech 11: 199-202

Cavidas AX, Trueta J (1965) An Experimental Study of the Vascular Contribution to the Callus of Fracture. Surg Gynecol Obstet 120: 731-47

Chao EYS, Briggs BT, McCoy MT (1979) Theoretical and Experimental Analyses of Hoffmann-Vidal External Fixation System. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 345-70

Charnley J (1953) Compression Arthrodesis. E and S Livingstone, Edinburgh.

Clancey GJ, Hansen ST (1978) Open Fractures of the Tibia. A review of One Hundred and Two Cases. J Bone Joint Surg 60A: 118-22

Clark ER, Clark EL (1942) Microscopic Observations on New Formation of Cartilage and Bone in the Living Mammal. Am J Anat 70: 167-200

Cole JM, Obletz BE (1966) Comminuted Fractures of the Distal End of the Radius Treated by Skeletal Transfixion in a Plaster Cast. An End-Result Study of Thirty-three Cases. J Bone Joint Surg 48A: 931-45

Cooney WP, Linscheid RL, Dobyns JH (1979) External Pin Fixation for Unstable Colles' Fractures. J Bone Joint Surg 61A: 840-5

Copp DH, Shim SS (1965) Extraction Ratio and Bone Clearance of SR^{85} as a Measure of Effective Bone Blood Flow. Circ. Res. 16: 461-7

Cucel LR, Rigaud R (1850) Des vis metalliques enfoncees dans les tissus des os, pour le traitement de certaines fractures. Rev Med Chir Paris 8: 115

Cumming JD (1962) A Study of Blood Flow through Bone Marrow by a Method of Venous Effluent Collection. J Physiol 162: 13-20

Currey JD (1969) The mechanical consequences of variation in the mineral content of bone. J Biomech 2: 1-11

Danis R (1949) Theorie et Practique de l'Osteosynthesis. Masson et Cie, Paris

De Bastiani G, Aldegheri R, Renzi Brivio L (1984) The treatment of fractures with a dynamic axial fixator. J Bone Joint Surg 66B: 538-45

De Bruyn PPH, Breen PC, Thomas TB (1970) The Microcirculation of the Bone Marrow. Anat Rec 168: 55-68

Dempster W (1955) Space requirements of the seated operator. WADC Technical Report 55: 159

Dickson RA (1975) Fixation of Unstable Metacarpal Fractures. The Hand 7: 284-6

Digby JM, Holloway GMN (1982) A Review of 100 Tibial Fractures Treated with Functional Bracing. J Bone Joint Surg 64B: 636

Donald GD, Seligson D (1982) Fixator Systems in Current Use. In: D Seligson, M Pope (eds) Current Concepts in External Fixation. Grune and Stratton, New York, pp 293-308

Edge AJ, Denham RA (1981) External Fixation for Complicated Tibial Fractures. J Bone Joint Surg 63B: 92-7

Edwards CC (1979) Management of the Polytrauma Patient in a Major U.S. Center. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 181-202

Eghker E, Martinek H, Wielke B (1980) How to increase the stability of external fixation units. Mechanical tests and theoretical studies. Arch Orthop Traumat Surg 96: 35-43

Ekelund A, Engesaeter LB, Langelang N (1981) Mechanical properties of fractured and intact rat femora evaluated by bending, torsional and tensile tests. Acta Orthop Scand 52: 605-13

Ellis H (1958) The Speed of Healing after Fracture of the Tibial Shaft. J Bone Joint Surg 40B 42-6

Ellis H (1958) Disabilities after Tibial Shaft Fractures. With Special Reference to Volkmann's Ischaemic Contracture. J Bone Joint Surg 40B: 190-7

Evans FG (1973) Mechanical Properties of Bone. Charles C. Thomas. Springfield Illinois

Evans M, Kenwright J, Tanner KE (1979) Analysis of single-sided external fracture fixation. Eng Med 8: 133-7

Evans M, Harris D (1982) The Mark 2 Controlled Movement Fixator. Annual Report of the Oxford Orthopaedic Engineering Centre, pp67-8

Fellander M (1963) Treatment of fractures and pseudarthroses of the long bones by Hoffmann's transfixion method (osteotaxis). Acta Orthop Scand 33: 132-50

Fischer DA (1982) External Fixation in the Management of the Open Fracture. In: RB Gustilo (ed) Management of Open Fractures and their Complications. WB Saunders, Philadelphia, pp 70-96

Fischer DA, Chao EYS, Cabanela ME (1980) Cortical bone union in external fixation. A clinical and biomechanical analysis. Scientific exhibit, American Academy of Orthopaedic Surgeons Annual Meeting, Atlanta

Fischer DA (1983) Skeletal Stabilisation with a Multiplane External Fixation Device. Design Rationale and Preliminary Clinical Experience. Clin Orthop 180: 50-62

Forgon M, Mammel E (1981) The External Fixateur in the Management of Unstable Colles Fracture. Int Orthop 5: 9-14

Frankel VH, Nordin M (1980) Basic Biomechanics of the Skeletal System. Lea and Febiger, Philadelphia

Freeman MAR, King JB, O'Riordan SM (1983) The Day Frame. In: BT O'Connor, CE Ackroyd, PF de Bruyn (eds) The Severely Injured Limb. Churchill Livingstone, Edinburgh, pp 129-43

Gotham L (1961) Vascular Reactions in Experimental Fracture. Microangiographic and Radioisotope Studies. Acta Chir Scand Suppl 284

Green SA (1981) Complications of External Fixation. Charles C. Thomas, Springfield Illinois

Grosse A (1979) Stabilisation of Pelvic Fracture with Hoffmann External Fixator: The French Experience. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 123-32

Gross PM, Marcus ML, Heistad DD (1981) Measurement of Blood Flow to Bone and Marrow in Experimental Animals by Means of the Microsphere Technique. J Bone Joint Surg 63A: 1028-31

Gurtl EJ (1857) Beitrage zur Statistik der Fracturen und Luxationen, enthaltend eine Ubersicht der in einem 5 jahrigen Zeitraune in den Berliner Hospitalern behandelten Fracturen und Luxationen. Deutsche Klinik Berl 9

Gustilo RB (1982) Management of Open Fractures and their Complications. WB Saunders. Philadelphia

Haarman HJ, Goudfrooy H, Roelofs JMM, Akkermans LMA, Wittebol P (1979) A comparative investigation into the mechanical properties of different external fixators, leading to the development of a new type external fixator. 2nd Meeting of the European Society of Biomechanics, Strasbourg

Ham AW (1930) Histological study of the early phases of bone repair. J Bone Joint Surg 12: 827-44

Harvey FG, Hodgkinson ATH, Harvey PM (1975) Intramedullary Nailing in the Treatment of Open Fractures of the Tibia and Fibula. J Bone Joint Surg 57A: 909-15

Haynes HH (1939) Treating Fractures by Skeletal Fixation of the Individual Bone. South Med J 32: 720-4

Hedley AK, Bernstein ML (1983) External fixation as a secondary procedure. Clin Orthop 173: 209-15

Heiple KG, Herndon CH (1966) The pathologic physiology of non-union. Clin Orthop 43: 11-21

Henderson NJ, Carvell JE, Cockin J (1983) The management of complex forearm fractures. Injury 14: 395-404

Henry A, Freeman MAR, Swanson SAV (1968) Studies on the mechanical properties of healing experimental fractures. Proc Roy Soc Med 61: 40-4

Heppenstall RB, Grisulis G, Hunt TK (1975) Tissue gas tensions and oxygen consumptions in healing bone defects. Clin Orthop 106: 357-65

Hey Groves EW (1921) On Modern Methods of Treating Fractures. 2nd ed, John Wright and Sons, Bristol

Heymann MA, Payne BD, Hoffman JIE, Rudolph AM (1977) Blood Flow Measurements with Radionuclide-labelled Particles. Proc Cardiovasc Dis 20: 55-79

Hoffmann R (1938) Rotules a os pour la reduction dirigee, non sanglante, des fractures (osteotaxis) Helv Med Acta 5: 844-50

Hughes JL, Sauer BW (1982) Wagner Apparatus: A Portable Traction Device. In: D Seligson, M Pope (eds) Current Concepts in External Fixation. Grune Stratton, New York, pp 203-18

Hughes SPF, Kahn RAA, Davies SDR, Lavender JP (1978) The Uptake By the Canine Tibia of the Bone-Scanning Agent ^{99m}TcMDP Before and After an Osteotomy. J Bone Joint Surg 60B: 579-82

Hughes SPF (1983) Personal Communication.

Hutchins PA (1981) The outcome of severe tibial injury. Injury 13: 216-9

Inoue S, Sakakida K, Imae M (1972) New external fixation method by rapidly polymerizing resin. Orthop Surg (Tokyo) 23: 149-54

Jackson RP, Jacobs RR, Neff JR (1977) External Skeletal Fixation in Severe Limb Trauma. J Trauma 18: 20q-5

Jager m, Gordes W, Kossyk W, Ugethum M (1976) Bruchfestigkeitsuntersuchungen bei konservativ und operativ behandelten Osteotomien der Kaninchen-Tibia. Unfallheilkunde 79: 193-201

Jenkins DHR, Young MH (1978) The operative treatment of sacro-iliac subluxation and disruption of the pubic symphysis. Injury 10: 139-41

Johnston HE, Stovald SL (1950) External Fixation of Fractures. J Bone Joint Surg 32A: 460-7

Johnston R (1979) Stabilisation of Pelvic Fractures with Hoffmann External Fixation: The Colorado Experience. AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 133-50

Johnston RW, Lyford J (1944) The Haynes Fixation Apparatus in Orthopaedic Surgery. J Bone Joint Surg 26: 475-82

Johnston WD, Fischer DA (1983) Skeletal Stabilisation with a Multiplane External Fixation Device. Biomechanical Evaluation and Finite Element Model. Clin Orthop 180: 34-43

Jorgensen TE (1972) Measurements of stability of crural fractures treated with Hoffmann osteotaxis. 2. Measurements on crural fractures. Acta Orthop Scand 43: 207-18

Judet H (1932) Instrumentation pour osteosynthese a tuteur externe. Bull Mem Soc Chir Paris 24: 400-5

Judet J, Judet R (1960) L' osteogenese et les retards de consolidation et les pseudarthroses des os longs. 8^e Congres SICOT 315

Kamhin M, Michaelson M, Waisbrod H (1977) The use of external skeletal fixation in the treatment of fractures of the humeral shaft. Injury 9: 331-3

Kane WJ, Grim E (1969) Blood Flow to Canine Hind-Limb Bone, Muscle and Skin. A Quantitative Method and its Validation. J Bone Joint Surg 51A: 309-22

Kaplan JZ, Pruitt BA (1980) Burns and Fractures. In: RB Heppenstall (ed) Fracture Treatment and Healing. WB Saunders, Philadelphia, p 992

Karlstrom G, Olerud S (1975) Percutaneous Pin Fixation of Open Tibial Fractures. Double-Frame Anchorage Using the Vidal-Adrey Method. J Bone Joint Surg 57A: 915-24

Karlstrom G, Lonnerholm T, Olerud S (1975) Cavus Deformity of the Foot after Fracture of the Tibial Shaft. J Bone Joint Surg 57A: 893-900

Keetley CB (1893) On the Prevention of Shortening and Other forms of Mal-union after Fracture. Lancet 1: 1377-9

Kelly PJ, Yipintsoi T, Bassingthwaite JB (1971) Blood Flow in Canine Tibial Diaphysis Estimated by Iodoantipyrine ¹²⁵I Washout. J Appl Physiol 31: 38-47

Kenwright J, Harris JD, Evans M (1979) External fracture fixation - the analysis and design of a new system. Eng Med 8: 138-42

Klemm K (1979) Treatment of Infected Non-Unions with Gentamycin-PMMA Beads and External Fixation. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 285-96

Krempen JF, Silver RA, Sotelo A (1979) The Use of the Vidal-Adrey External Fixation System. Part 1. The Treatment of Open Fractures. Clin Orthop 140: 111-21

Krempen JF, Silver RA, Sotelo A (1979) The Use of the Vidal-Adrey External Fixation System. Part 2. The Treatment of Infected and Previously Infected Pseudarthroses. Clin Orthop 140: 122-30

Krompecher I (1937) Die Knochenbildung. Gustav Fischer Verlag, Jena

Kuntscher G (1962) Praxis der Marknagelung. Schattauer, Stuttgart

Lambotte A (1913) Chirurgie Operatoire des Fractures. Masson et Cie, Paris

Lambret O (1910) Appereil pour la reduction et la contention des fractures. Bull Mem Soc Chir Paris 2: 871-5

Lanyon LE, Hampson WGJ, Goodship AE, Shah JS (1975) Bone deformation record in vivo from strain gauges attached to the human tibial shaft. Acta Orthop Scand 46: 258-68

Lawyer RB, Lubbers LM (1979) Use of the Hoffmann Apparatus in the Treatment of Unstable Tibial Fractures. J Bone Joint Surg 62A; 1264-73

Leach RE (1975) Fractures of the Tibia. In: CA Rockwood, DP Green (eds) Fractures. JP Lippincott, Philadelphia, pp 1285-1360

Letournel E (1982) The Judet Fixateur for Fractures of the Ankle. In: D Seligson, M Pope (eds) Current Concepts in External Fixation. Grune and Stratton, New York, pp 247-66

Lindahl O (1962) Rigidity of immobilisation of transverse fractures. Acta Orthop Scand 32: 237-46

Lopez Curto JA, Bassingthwaite JB, Kelly PJ (1980) Microvasculature of the Tibial Diaphysis of the Adult Dog. J Bone Joint Surg 62A: 1362-9

Lottes JO, Hill LJ, Key AJ (1952) Closed reduction, Plate Fixation and Medullary Nailing of Fractures of Both Bones of the Leg. J Bone Joint Surg 34A: 861-77

Lunde PKM, Michelsen K (1970) Determination of Cortical Blood Flow in Rabbit Femur by Radioactive Microspheres. Acta Physiol Scand 80: 39-44

Malgaigne J (1853) Considerations cliniques sur les fractures de la routule et leur traitement par os griffes. J Conn Med Prat 16: 9-12

Marcus ML, Heistad DD, Ehrhardt JC, Abboud FM (1976) Total and Regional Cerebral Blood Flow Measurement with 7-, 10-, 15-, 25- and 50 um Microspheres. J Appl Physiol 40: 501-7

Mazet R (1943) The Use and Abuse of the Anatomic Splint in the Treatment of Fractures of the Lower Extremity. J Bone Joint Surg 25: 839-58

McCarthy I (1983) Personal Communication

McCoy MT, Briggs BT, Chao EYS (1980) A comparative study of external fixators based on bone fracture stiffness. Proceedings of the 26th Annual Orthopedic Research Society, Atlanta

McElfresh EC, Kelly PJ (1974) Simultaneous Determination of Blood Flow in Cortical Bone, Marrow and Muscle in Canine Hind Leg by Femoral Artery Catheterisation. *Calcif Tiss Res* 14: 301-7

McKibben B (1978) The Biology of Fracture Healing in Long Bones. *J Bone Joint Surg* 60B: 150-62

Mears DC (1979) The Use of External Fixation in Arthrodesis. In: AF Brooker, CC Edwards (eds) *External Fixation The Current State of the Art*. Williams and Wilkins, Baltimore, pp 241-76

Mears DC (1979) The Management of Complex Pelvic Fractures. In: AF Brooker, CC Edwards (eds) *External Fixation The Current State of the Art*, Williams and Wilkins, Baltimore, pp 151-80

Mears DC, Fu FH (1980) Modern Concepts of External Skeletal Fixation of the Pelvis. *Clin Orthop* 151: 65-72

Morgan JD (1959) Blood Supply of Growing Rabbit's Tibia. *J Bone Joint Surg* 41B: 185-203

Morris MA, Kelly PJ (1980) Use of Tracer Microspheres to Measure Bone Blood Flow in Conscious Dogs. *Calcif Tiss Int* 32: 69-76

Muller ME (1965) Treatment of Non-unions by Compression. *Clin Orthop* 43: 83-92

* Muller ME, Allgower M, Willenegger H (1970) *Manual of External Fixation*. Springer Verlag, New York

Muller ME, Thomas R (1979) Treatment of non-unions in fractures of the long bones. Clin Orthop 138: 141-53

Muller ME, Allgower M, Schneider R, Willenegger H (1979) Manual of Internal Fixation. Techniques recommended by the AO Group. 2nd ed. Springer Verlag, Berlin Heidelberg

Nelson GE, Kelly PJ, Peterson LFA, Janes JM (1960) Blood Supply to the Human Tibia. J Bone Joint Surg. 42A: 625-36

Nicoll EA (1964) Fractures of the Tibial Shaft. J Bone Joint Surg 46B: 373-8

Oganesyan OV (1982) Use of the Volkov-Oganesyan Hinge Distractor to Restore Joint Function. In: D Seligson, M Pope (eds) Current Concepts in External Fixation. Grune and Stratton, New York, pp 139-70

Olerud S (1979) Unusual Indications for External Fixation with the Hoffmann Device. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 297-316

Olerud S, Dankwardt-Lillestrom G (1968) Fracture Healing in Compression Osteosynthesis in the Dog. J Bone Joint Surg 50B: 844-51

Olerud S, Dankwardt-Lillestrom G (1971) Fracture healing in compression osteosynthesis. An experimental study in dogs with an avascular, diaphyseal, intermediate fragment. Acta Orthop Scand (Suppl) 137: 1-44

Olerud S, Karlstrom G (1972) Tibial fractures treated by AO compression osteosynthesis. Acta Orthop Scand (Suppl) 140: 3-44

Ordway CB (1982) Application of External Fixation to the Tibia. In: D Seligson, M Pope (eds) Current Concepts in External Fixation. Grune and Stratton, New York, pp 219-46

Paavolainen P, Slatis P, Karaharju E, Holmstrom T (1979) Healing of experimental fractures by compression osteosynthesis. 1. Torsional strength. Acta Orthop Scand 50: 369-74

Papineau L (1973) L'excision greffe avec fermeture cutanee retardee delib, aaeree dans l'osteomyelite chronique. Nouvelle Presse Medicale 2: 1753-5

Paradis GR, Kelly PJ (1975) Blood Flow and Mineral Deposition in Canine Tibial Fractures. J Bone Joint Surg 57A: 220-6

Parkhill C (1898) Further observations regarding the use of the bone clamp in ununited fractures, fractures with malunion and recent fractures with a tendency to displacement. Ann Surg 27: 553-70

Perren SM, Huggler A, Russenberger M, Allgower M, Mathys R, Schenk R, Willenegger H, Muller ME (1969) The Reaction of Cortical Bone to Compression. Acta Orthop Scand (Suppl) 125: 19-28

Phemister DB (1947) Treatment of Ununited Fractures by Onlay Bone Grafts without Screw or Tie Fixation and without Breaking Down the Fibrous Union. J Bone Joint Surg 29: 946-60

Post M, Shoemaker WC (1964) Method for Measuring Bone Metabolism in Vivo. J Bone Joint Surg 46A: 111-20

Pritchard JJ (1963) Hard tissues - bone and bones. In: F Goldly, RJ Harrison (eds) Recent Advances in Anatomy. 2nd Series. J and A Churchill, London, pp 204-36

Putti V (1921) The operative lengthening of the femur. JAMA 77: 934-5

Radin EL, Simon SR, Rose RM, Paul IL (1979) Practical Biomechanics for the Orthopaedic Surgeon. Jan Wiley and Sons, New York.

Rahn BA, Gallinaro P, Baltensperger A, Perren SM (1971) Primary Bone Healing. An Experimental Study in the Rabbit. J Bone Joint Surg 53A: 783-6

Ramadier JO, Lecestre P, Camilleri A, Bombart M, Mazas F, Witvoet J, Zucman J (1981) Fractures ouvertes de jambe. Etude de 818 cas. Int Orthop 5: 169-82

Rezaian SM (1971) The Effect of a New External Bone-Fixator on the treatment of Fractures of Long Bones. Ann Roy Coll Surg Eng 48: 336-43

Rhineland FW (1972) Circulation in Bone. In: GH Bourne (ed) The Biochemistry and Physiology of Bone. 2nd Ed. Academic Press, New York, pp 1-77

Rhineland FW (1974) Tibial blood supply in relation to fracture healing. Clin Orthop 105: 34-81

Rhineland FW, Baragy (1962) Microangiography in Bone Healing. 1. Undisplaced Closed Fractures. J Bone Joint Surg 44A: 1273-98

Rhineland FW, Phillips RS, Steel WM, Beer JC (1968) Microangiography in Bone Healing. 2. Displaced Closed Fractures. J Bone Joint Surg 50A: 643-62

Rhineland FW, Wilson JW (1982) Blood Supply to Developing, Mature and Healing Bone. In: G Sumner-Smith (ed) Bone in Clinical Orthopaedics. A Study in Comparative Osteology. WB Saunders, Philadelphia, pp 81-158

Ronen GM, Michaelson M, Waisbrod H (1974) External fixation in war injuries. Injury 6: 94-8

Rosen H (1979) Compression Treatment of Long Bone Pseudarthroses. Clin Orthop 138: 154-66

Roy Camille R, Reignier B, Saillant G, Berteaux D (1976) Resultats de l'operation de Papineau. Rev Chir Orth 62: 347-62

Sahlstrand T (1979) Disruption of the Pelvic Ring Treated by External Skeletal Fixation. J Bone Joint Surg 61A: 433-4

Sarmiento A (1967) Below the Knee Cast for Tibial Fractures. J Bone Joint Surg 49A: 855-75

Sarmiento A, Schaeffer JF, Beckerman L, Latta L, Enis J (1977) Fracture Healing in Rat Femora as Affected by Functional Weight-Bearing. J Bone Joint Surg 59A 369-75

Schenk R, Willenegger H (1967) Morphological findings in primary bone healing. Symp Biol Hung 7: 75-86

Schroder HA, Frandsen PA (1983) External Compression Arthrodesis of the Shoulder Joint. Acta Orthop Scand 54: 592-5

Seligson D, Kristiansen TK (1978) Use of the Wagner Apparatus in Complicated Fractures of the Distal Femur. J Trauma 18: 795-9

Seligson D, Powers G, O'Connell P, Pope MH (1981) Measurement of Fracture Gap Motion in External Fixation. J Trauma 21: 798-801

Sevitt S (1981) Bone Repair and Fracture Healing in Man. Churchill Livingstone, Edinburgh

Shaar CM, Kreuz FP, Jones DT (1944) End Results of Treatment of Fresh Fractures by the Use of the Stader Apparatus. J Bone Joint Surg 26: 471-4

Sheridan GW, Matsen FA (1976) Fasciotomy in the Treatment of the Acute Compartment Syndrome. J Bone Joint Surg 58A: 112-5

Sissons HA, Hadfield GJ (1951) The influence of cortisone on the repair of experimental fractures in the rabbit. Brit J Surg 39: 172-8

Slatis P, Karaharju EO (1980) External Fixation of Unstable Pelvic Fractures: Experiences in 22 Patients Treated with a Trapezoid Compression Frame. Clin Orthop 151: 73-80

Souter WA (1969) Autogenous Cancellous Strip Grafts in the Treatment of Delayed Union of Long Bone Fractures. J Bone Joint Surg 51B: 63-75

Southwick WO (1967) Osteotomy Through the Lesser Trochanter for Slipped Capital Femoral Epiphysis. J Bone Joint Surg 49A 807-35

Stader O (1937) A Preliminary Announcement of a New Method of Treating Fractures. N Am Vet 18: 37-8

Sukhtian W, Hughes SPF (1979) An external fixation device: preliminary communication. J Roy Soc Med 72: 831-4

Tayton K, Johnson-Nurse C, McKibben B, Bradley J, Hastings G (1982) The Use of Semi-Rigid Carbon-Fibre-Reinforced Plastic Plates for Fixation of Human Fractures. Results of Preliminary Trials. J Bone Joint Surg 64B: 105-11

Terjesen T, Benum P (1983) In vitro effects of external fixation on intact and osteotomised tibiae. Acta Orthop Scand 54: 212-9

Thunold J, Varhaug JE, Bjerkeset T (1975) Tibial shaft fractures treated by rigid internal fixation. Injury 7: 125-33

Tile M (1984) Fractures of the Pelvis and Acetabulum. Williams and Wilkins, Baltimore.

Trueta J (1966) Non-union of Fractures. Clin Orthop 43: 22-36

Trueta J, Harrison MHM (1953) The Normal Vascular Anatomy of the Femoral Head in Man. J Bone Joint Surg 35B: 442-61

Trueta J, Cavidas AX (1955) Vascular Changes Caused by the Kuntscher Type of Nailing. J Bone Joint Surg 37B: 492-505

Trunkey DD, Chapman MW, Lim RC, Englebert D (1974) Management of Pelvic Fractures in Blunt Trauma Injury. J Trauma 14: 912-23

Uhthoff HK, Dubuc FL (1971) Bone structure changes in the dog under rigid internal fixation. Clin Orthop 81: 165-70

Uhthoff HK, Bardos DI, Liskova-Kiar M (1981) The Advantages of Titanium Alloy over Stainless Steel Plates for the Internal Fixation of Fractures. An Experimental Study in Dogs. J Bone Joint Surg 63B: 427-34

Uthoff HK, Finnegan M (1983) The Effects of Metal Plates on Post-traumatic Remodelling and Bone Mass. J Bone Joint Surg 65B: 66-71

Urist MR, McLean FC (1941) Calcification in the Callus in Healing Fractures in Normal Rats. J Bone Joint Surg 23: 1-16

Urist MR, Wallace TH, Adams T (1965) The function of fibrocartilaginous fracture callus. Observations on transplants labelled with tritiated thymidine. J Bone Joint Surg 47B: 305-18

Velazco A, Whitesides TE, Fleming LL (1983) Open Fractures of the Tibia Treated with the Lottes Nail. J Bone Joint Surg 65A: 879-84

Velazco A, Fleming LL (1983) Open Fractures of the Tibia Treated by the Hoffmann External Fixator. Clin Orthop 180: 125-32

Vidal J, Rabischong P, Boneel F (1970) Etude biomechanique du fixateur externe d'Hoffmann dans les fractures de jambe. Soc Chir Montpellier Seance 20 Jan:43-52

Vidal J, Connes H, Buscayret C, Trouillas J (1979) Treatment of Infected Non-Unions by External Fixation. In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 277-84

Vidal J, Buscayret C, Connes H (1979) Treatment of Articular Fractures by "Ligamentotaxis". In: AF Brooker, CC Edwards (eds) External Fixation The Current State of the Art. Williams and Wilkins, Baltimore, pp 75-82

Wagner H (1971) Operative beinverlangerung. Chirurg 42: 260-6

Wagner H (1977) Surgical Lengthening or Shortening of Femur and Tibia. Technique and Indications. In: DS Hungerford (ed) Leg Length Discrepancy. Springer Verlag, Berlin Heidelberg, PP 71-96

Wagner HN, Rhodes BA, Sasaki Y, Ryan JP (1969) Studies of the Circulation with Radioactive Microspheres. Invest Radiol 4: 374-86

Weir JB de V, Bell GH, Chambers JW (1949) The Strength and Elasticity of Bone in Rats on a Rachitogenic Diet. J Bone Joint Surg 31B: 444-51

Whiston G (1953) Internal Fixation for Fractures and Dislocations of the Pelvis. Injury 35A: 701-6

White AA, Panjabi MM, Hardy RJ (1974) Analysis of mechanical symmetry in rabbit long bones. Acta Orthop Scand 45: 328-36

White AA, Panjabi MM, Southwick WO (1977) The Four Biomechanical Stages of Repair. J Bone Joint Surg. 59A: 188-92

Wray JB, Lynch CJ (1959) The Vascular Response to Fractures of the Tibia in the Rat. J Bone Joint Surg 41A: 1143-8

Ya PM, Guzman T, Loken MK, Perry JF (1961) Isotope localisation with tagged microspheres. Surgery 49: 644-50

Yamagishi M, Yoshimura Y (1955) The Biomechanics of Fracture Healing. J Bone Joint Surg 37A: 1035-68

Zadek RE, Robinson RA (1961) The Effect of Growth Hormone on Healing of Experimental Long-Bone Defect. J Bone Joint Surg 43A: 1261